School of Land and Food

Formation, management and consequences of soil crusting in leafy packet salad production

By

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Abstract

The south east of Tasmania produces a large proportion of Australian packet salad. Intensive production with frequent cultivation on sandy clay loam soils has resulted in severe erosion, with soil crusting and low irrigation efficiency. Crust formation is common on cultivated soils, occurring in a wide variety of soil types, climates and agricultural practices. Soil crusts form as a thin, dense, low hydraulic conductivity layer on the soil surface that reduces infiltration, increases runoff and restricts seedling emergence. The objective of this study was to: (i) evaluate different approaches for measuring aggregate stability and the severity of soil crusting, (ii) identify mechanisms responsible for aggregate breakdown and crust formation, (iii) identify which soil properties contribute to aggregate stability/instability, (iv) evaluate options for reducing soil crusting, and (v) quantify the physical properties of soil crusts.

Soil samples were collected from 20 sites over five farms all managed for packet salad production. Aggregate stability was measured by rainfall simulation, wet sieving, ultrasonic vibration (dry and moist aggregates) and clay dispersion (dry aggregates). The mechanisms responsible for aggregate breakdown were investigated by comparing the effect of different wetting fluids on dry aggregate stability. Chemical, mineralogical and physical soil characteristics were measured to identify the soil properties related to aggregate stability/instability. The different methods by which aggregate stability were measured were poorly correlated with each other. This suggested that each approach applied a different type of disruptive energy to the aggregates such that the method of assessment needs to be matched to the type by field soils. Aggregate breakdown largely resulted from slaking by clay swelling and raindrop impact, and to a lesser extent clay dispersion and air compression. Aggregate stability determined by rainfall simulation was highly correlated with soil properties that promote aggregation such as the effective

cation exchange capacity (ECEC) and the proportion of polyvalent cations, whilst aggregate stability determined by wet sieving was highly correlated with soil properties that promote disaggregation such as sand content and to lesser extent, the proportion monovalent cations especially exchangeable K.

Two experiments were undertaken to evaluate the potential of commercially available products to reduce soil crusting. A preliminary experiment evaluated 11 products, with the four most effective products included in a second experiment. The second experiment compared application of paper waste, gypsum, phosphoric acid and wire mesh, at three different rates and various combinations. Soil chemical and physical properties were monitored over 71 days to understanding how soil crust developed and what changes in soil physical properties occurred over time. Paper waste and gypsum significantly reduced the severity of soil crusting relative to the control. However, these reductions in crusting were minor, as no product was able to adequately prevent crusting. Physical and hydrological properties indicated that about 80 % of soil crust formation was found after 9 rainfall or irrigation events.

In summary, management options for improving aggregation appear limited as aggregate stability was mostly related to inherent soil properties such as sand/quartz content. Application of paper waste and gypsum reduced the severity of crust formation, however no product was able to adequately prevent crusting. Data collected in this study are expected to enable development of soil crusting routines to improve soil water models.

Statement of Co-Authorship

The following people and institutions contributed to the publication of work undertaken as part of this thesis:

Abbas Almajmaie, School of Land and Food, University of Tasmania, Australia (Candidate)

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Paper 1: Evaluation of methods for determining soil aggregate stability

Submitted to Soil and Tillage Research, undergone two rounds of review, the revised manuscript was submitted in 30 August 2016, currently awaiting editor's decision on publication, located in chapter 2.

Abbas Almajmaie contributed 70% conceived and designed the manuscript including all field, experiment and analytical components, and wrote the manuscript, Marcus Hardie contributed 20 % (guided experimental design, advised statistical analysis, revised the manuscript), Tina Acuna and Colin Birch contributed 5% equally (revised the manuscript).

Paper 2: Influence of soil properties on the aggregate stability of cultivated sandy clay loams

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Abbas Almajmaie contributed 65% conceived and designed the manuscript including all field, experiment and analytical components, and wrote the manuscript, Marcus Hardie contributed 20 % (guided experimental design, advised statistical analysis, revised the manuscript), Tina Acuna, Colin Birch and Richard Doyle contributed 5% equally (provided critical analysis of the manuscript).

Paper 3: Can soil crusting be reduced through application of gypsum, organic waste and phosphoric acid?

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Abbas Almajmaie contributed 60% (conducted the experiment and analysed the data, conceived and designed the paper and wrote the manuscript), Marcus Hardie contributed 30 % (guided experimental design, advised statistical analysis, revised the manuscript), Tina Acuna and Colin Birch contributed 5% equally (revised the manuscript).

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Table of content

List of Figures

List of Tables

List of plates

Chapter 1: General Introduction

1.1 Soil crusting

Formation of soil crusting is a world-wide phenomenon occurring in a variety of soil types and climatic conditions (Sumner & Miller 1992, Valentin & Bresson 1992). Houston's Farm is one of the most successful farming enterprises in southern Tasmania. They supply packet salad to more than 1200 major supermarkets across Australia. To meet this demand, the cropping system requires up to 12 cultivations a year to incorporate residues from the previous crop, reshape and prepare a seed bed. Additional traffic also occurs during sowing, spraying and harvesting. Crops are irrigated every second day over summer, in which the average irrigation is about 2.5 ML/ha per year. The production system is very intensive, with the short cropping sequence requiring considerable soil working, leading to formation of soil crusting. These crusts reduce infiltration, promote ponding and runoff, and result in poor irrigation performance and soil erosion (Hardie et al. 2013).

Soil crusts are characterised by the formation of a thin and dense layer at the soil surface, which has less porosity and higher penetration resistance than the lower soil layers (Valentin & Bresson 1997). Crusting results in a range of agronomic and environmental issues including reduced rainfall effectiveness and irrigation efficiency, poor seedling emergence, increased runoff, surface ponding and erosion (Moss 1991, Carmi & Berliner 2008).

1.2 Types of soil crusts

Three different types of soil crusts have been described: physical, biological and chemical crusts (Rattan & Shukla 2004). This study only considers the formation of physical crusts including both structural and depositional forms of physical crusts (Chen

et al. 1980, Singer 1991). Structural crusts occur as a result of rainfall impact, which lead to aggregate dispersion and clogging of soil pores by fine particles, whilst depositional crusts occur when fine particles are deposited on the soil surface by overland flow (Bu et al. 2013). According to Chen et al. (1980) formation of soil structural crusts occurs in three stages. Firstly, when soil particles are exposed to rainfall, fine soil particles start to separate from coarse particle due to the impact of rain droplets. Subsequently, the fine particles are drawn into the soil by the infiltrating rainwater resulting in clogging of pore spaces and the formation of a dense, thin layer on the soil surface. McIntyre (1958) reported that structural crusts include two distinct parts: (i) a surface skin (0.1 mm thick), which is mostly produced by raindrop impact and (ii) a washed-in zone (up to 3 mm thick), which is characterized by low porosity because of the deposition of mobilized fine material in pores.

1.3 Formation of soil crusts

Aggregate breakdown to form soil crusts results from a combination of physico-chemical and physical mechanisms in which the kinetics of the breakdown process, interparticle bonds and energy involved in disaggregation differ between different soil types including different in mineralogy, chemistry and structure (Kemper & Rosenau 1984, Truman et al. 1990). Mechanisms of aggregate breakdown include (i) breakdown from raindrop impact (Nearing & Bradford 1985); (ii) slaking by air compression during wetting (Le Bissonnais & Arrouays 1997), (iii) slaking by differential clay swelling (Le Bissonnais et al. 1989); and (iv) physico-chemical dispersion due to osmotic stress (Emerson 1967, Shainberg 1992, Sumner 1992).

1.3.1 Raindrop impact

The extent to which raindrop impact influences crust formation also depends on rainfall properties such as the amount and intensity of rainfall, together with rain drop size and raindrop velocity at impact (Truman et al. 2007, Augeard et al. 2008, Fan et al. 2008). According to Terry (1992) and Gholami et al. (2013), rain droplets disaggregate soils in a series of steps or processes including; (i) physical impact of rain droplets; (ii) detachment of soil particles; (iii) displacement of soil particles (iv) clogging of soil pores, and (v) reduction in infiltration following by increased runoff and erosion. Jimba and Lowery (2010) reported raindrop impact has greater effects on disaggregation than other forces. Detachment and splash usually increase with droplet size due to the increased kinetic energy (Furbish et al. 2007). As fine particles are detached, they are drawn into soil pores, which become clogged forming a soil seal or crust on drying (Bu et al. 2013).

1.3.2 Slaking

Slaking has been reported as the dominant mechanism responsible for aggregate breakdown in clay soil (Emerson 1964). Slaking usually results from a combination of both air compression and clay swelling (Le Bissonnais 1996). Disaggregation by slaking has been shown to be influenced by clay type and clay content (Ben-Hur & Lado 2008, Reichert et al. 2009). Reichert et al. (2009) reported that slaking is higher in clays rich in kaolinite and oxyhydroxides of Fe and Al, and lowest in 2:1 clays rich in montmorillonite, illite, and smectite. Yoder (1936) explained that when water enters a soil aggregate, differential swelling leads to crack boundaries that form in areas of lowest shear strength. Thin layers of absorptive water that are held by the colloidal surfaces become thicker causing the clay platelets to be pushed apart. Swelling also

results in softening of aggregates that become more susceptible to disaggregation by air compression.

Slaking by air compression results from compression of air trapped inside aggregates during wetting (Emerson 1967). Slaking by air compression mostly occurs in dryer aggregates, following sudden immersion in water (Soil Quality 2011). The extent to which aggregates are susceptible to slaking by air compression depends on the soil porosity, pore structure, the rate of wetting and the shear strength of the wet aggregates (Nearing & Bradford 1985, Loch 1994). Air compression is caused by water rapidly entering the aggregate via large capillary passages causing the air within the aggregates to be entrapped by the advancing water in mostly smaller pores. This causes the soil air to become compressed resulting in a series of miniature explosions, which shatter the aggregates into smaller fragments (Truman et al. 1990). Disaggregation by raindrop impact or slaking may also be followed by clay dispersion.

1.3.3 Dispersion

Clay dispersion is commonly associated with soil crusting and clogging of conducting pores in both surface and subsurface soils (Frenkel et al. 1992, Mbagwu & Schwertmann 2006). The degree of clay dispersion depends on (i) clay charge characteristics, (ii) cation ratios especially the exchangeable sodium percentage (ESP), (iii) the electrolyte concentration of infiltration water (Emerson 1967, Agassi et al. 1981, Agassi et al. 1985, Römkens et al. 1990, Le Bissonnais 1996, Marchuk et al. 2012), and (iv) attractive forces between colloidal particles (Emerson 1967, Sumner 1992). Paes et al. (2013) reported that clay dispersion increases as ESP increases and the electrical conductivity decreases.

Electrolyte concentration plays a crucial role in the process of aggregate breakdown in soils exposed to crusting. During rainfall or an irrigation event, the low concentration of electrolytes with high value of exchangeable Na^+ (ESP > 6) may result in soil crusting (Shainberg & Letey 1984, Suarez et al. 1984, Amezketa & Aragues 1995b, a). Rengasamy and Olsson (1991) showed that soil aggregates are more susceptible to dispersion when SAR are greater than 3 and the electrolyte concentration is less than a threshold value. Soils with high values of exchangeable Na^+ (ESP > 6) may disperse and resulting in reduced soil drainage, increased runoff and erosion (So & Aylmore 1993, Menneer et al. 2001, Keren & Ben-Hur 2003). Mamedov et al. (2002) stated that there is a linear correlation between runoff and ESP that becomes exponential at higher values. However, soil dispersion has been reported to occur in soils with ESP < 6 (Oster et al. 1980, Crescimanno et al. 1995, Curtin et al. 1995, Levy & Torrento 1995, Kaplan et al. 1996, Levy et al. 2005).

Soil dispersion may also result from high levels of exchangeable potassium. Auerswald et al. (1996) has reported that soil disaggregation is more likely to happen in soils with high exchangeable potassium percentage (EPP) than in soils with low EPP. In much the same way Na^+ influences dispersion, K^+ as a monovalent cation also contributes to aggregate breakdown by facilitating swelling and dispersion (Igwe & Okebalama 2006, Rengasamy 2010, Rengasamy & Marchuk 2011). Although K^+ has been reported as a dispersive cation, however several studies have shown potassium to have no contribution to soil dispersion (Levy & Torrento 1995, Dufranc et al. 2004, Laurenson et al. 2011, Ribeiro et al. 2013). As such the effect of K^+ on aggregate breakdown is not yet resolved and in all likelihood is soil specific.

1.4 Aggregating factors

1.4.1 Organic matter

Soil organic matter has been widely reported as the dominant soil property responsible for promoting the formation and stabilization of soil aggregates (Tisdall & Oades 1982, Chaney & Swift 1984, Chenu et al. 2000). Many of the process that are attributed to disaggregation and loss of soil structure resulted from loss of soil carbon (Garcia-Orenes et al. 2005). The mechanism by which organic matter influences soil aggregation is understood to be size dependant (Tisdall & Oades 1982). Micro-aggregates including primary mineral particles are linked to each other with bacterial, fungal and plant residue. Macro-aggregates are formed by linking micro-aggregates together by transient binding agents such as plant-derived polysaccharides (Six et al. 2000). It has been reported that the aggregating agents within micro-aggregates are stronger than the aggregating agents between micro-aggregates (Edwards & Bremner 1967). Organic carbon also has been reported to have decreased the wetting rate of soil aggregates, which lead to reduced slaking by rapid wetting (Sullivan 1990, Leelamanie et al. 2013). Organic matter also promotes stability of soil aggregates by increasing the electrolyte concentration, as disaggregation was reported to occur in soil with low electrolyte concentration (Piccolo & Mbagwu 1990, Amezketa & Aragues 1995b).

1.4.2 Polyvalent cations

Soils with high contents of polyvalent cations, Fe^{3+}, Al^{3+} and Ca^{2+} tend to promote aggregation (McNeal et al. 1966, Keren & Singer 1989). Iron oxides increase aggregate stability by acting as aggregating agents due to the attraction between positive charged Fe-oxides and negative charged clay particles (Rampazzo et al. 1999, Igwe et al. 2009). Different forms of Al^{3+} such as hydroxide, chloride and hydroxy ions may also act as stabilizing agents by decreasing swelling and dispersion (Alperovitch et al. 1985, Keren

& Singer 1989, Beppu et al. 1992, Igwe et al. 2009). Moreover, exchangeable Ca^{2+} has also been reported to influence flocculation of clays (Dontsova & Norton 2002). Chi et al. (1977) reported that disaggregation can be reduced when small amount of Na^{+} is replaced by Ca^{2+}.

1.5 Measurement of crusting severity

1.5.1 Aggregate stability

The risk or likelihood that a soil will form a surface crust may be inferred by measuring aggregate stability (Le Bissonnais 1996, Materechera 2009). Aggregate stability measures the capability of soil aggregates to resist disaggregation or breakdown to smaller particles, which result in the formation of soil crusts (Amezketa et al. 2003). Aggregate stability has been measured by many different methods, such as wet sieving, rainfall simulation, ultrasonic disruption and clay dispersion (Kemper & Rosenau 1986, Le Bissonnais 1996, Emerson 2002, Fristensky & Grismer 2008). The selection of an appropriate method or procedure for determining aggregate stability is not straight forward. In theory, selection should be based on the purpose of the analysis, soil type, as well as the type and level of disruptive energy that soil aggregates experience in the field (Herrick et al. 2001).

The most common method of determining aggregate stability is wet sieving. However this method has been criticised as it does not take into account all possible mechanisms responsible for aggregate breakdown, specifically raindrop impact. Furthermore, it tends to overemphasise breakdown by slaking, whilst not allowing sufficient time for dispersion and flocculation (Kemper & Rosenau 1986). Le Bissonnais (1996) developed the ‘unified framework’ wet sieving procedure, which includes use of both water and ethanol as wetting fluids, together with slow and fast rates of wetting, and mechanical

energy (shaking after pre-wetting). By comparing values of aggregate stability of different treatments, the procedure is able to infer the proportion of disaggregation resulting from different mechanisms of aggregate breakdown. Whilst the unified approach is more comprehensive than traditional wet sieving approaches, the procedure is complicated, involves multiple tests, and does not appear to be widely adopted by subsequent researchers. Furthermore, wet sieving procedures, including the unified framework do not consider the effect of raindrop bombardment on disaggregation, and are usually conducted over too short a duration to allow for dispersion to be complete.

A number of approaches have been developed to measure aggregate stability by rainfall simulation. Ideally rainfall simulation should apply similar sized droplets, at similar levels of energy, as what aggregates are exposed to in the field. Review of the literature however indicates that a broad range of droplet sizes, drop heights and rainfall intensity have been used to determine aggregate stability (McCalla 1944, Low 1954, Morin & Benyamini 1977, Norton 1987, An et al. 2012).

Ultrasonic vibration has also been used to measure aggregate stability (Imeson & Vis 1984, Mentler et al. 2004, Fristensky & Grismer 2008, Zhu et al. 2009, Rawlins et al. 2013). Sonication creates cavitation, the formation of an empty space or bubbles within soil aggregates and water. As these bubbles expand they rupture the soil along cracks and lines of weakness, leading to cleavage of aggregates into smaller fragments or primary particles (Kaiser & Asefaw Berhe 2014). Whilst sonication is a very effective means of disaggregating soils, the procedure is difficult to relate to the behaviour of field soils.

Field aggregates may also break down by dispersion, especially if they contain sodic clays. Dispersion tends to occur over longer durations than allowed for by most

procedures such as wet sieving and rainfall simulation and thus its importance may be underestimated. Clay dispersion may be measured using qualitative and quantitative tests (Emerson 2002), in which the turbidity or the amount of suspended clay is compared between different fluids or levels of agitation (Rengasamy et al. 1984).

1.6 Physical measures of soil crusts

The severity of crust formation can be inferred from the effect of soil crusts on hydrological measurements such as infiltration, runoff, as well as penetration resistance, surface density and surface soil porosity (Agassi et al. 1985, Sumner & Miller 1992, Pham et al. 2012, Drahorad & Felix-Henningsen 2013, Souza et al. 2014, Nciizah & Wakindiki 2016). A number of studies have inferred the severity of soil crusting from penetration resistance (Cresswell & Hamilton 2002, Drahorad & Felix-Henningsen 2013, Pulido et al. 2014). Penetration resistance is a simple, inexpensive, rapid, means to infer crust severity, and is closely related to the difficulty that seedlings experience during emergence (Clark & David 2008). However, values of penetration resistance are also closely related to soil moisture content (Tarkiewicz & Nosalewicz 2005, Pham et al. 2012), such that results are difficult to compare over time or between treatments. As soil crusting influences water infiltration and hydraulic conductivity, hydrological tests can be used as surrogate for measuring by the severity of soil crusting (Valentin & Bresson 1997, Nciizah & Wakindiki 2015). Many studies have used infiltration rate or hydraulic conductivity to measure the development or severity of soil crusting (Assouline & Mualem 2001, Assouline 2004, Pulido et al. 2014). Devices such as tension or sprinkler infiltrometer, and mobile rainfall simulation have been used to infer the effect of crust formation on hydraulic conductivity. However, these measurements are cumbersome, time-consuming and expensive.

1.7 Management of soil crusting

Review of the literature suggests that management systems that restore soil organic matter, increase electrolyte concentration and decrease raindrop impact are likely to reduce aggregate breakdown and crust formation (Wallace & Wallace 1986, Levy et al. 1995, Haynes & Naidu 1998, Portella et al. 2012). Organic matter acts as an aggregating agent, reduces wetting rate, increases electrolyte concentration and improves soil hydrological properties (Tisdall & Oades 1982, Wuddivira & Stone 2006, Leelamanie et al. 2013). However, the use of animal based composts and manure is prohibited in the Houston's production system due to food safety concerns.

Previous studies have reported that application of gypsum can reduce clay dispersion and crust formation in sodic soils (Verba & Devyatykh 1992, Qadir et al. 1996, Chorom & Rengasamy 1997, Ellington et al. 1997, Ilyas et al. 1997). Application of gypsum acts by replacing exchangeable Na^{+} with Ca^{2+}, and by increasing electrolyte concentration in the soil water (Quirk & Schofield 1955, Awadhwal & Thierstein 1985, Valzano et al. 2001), which leads to decreased clay dispersion and crust formation (Verba & Devyatykh 1992, Qadir et al. 1996, Chorom & Rengasamy 1997, Ellington et al. 1997, Ilyas et al. 1997). Initial chemical analysis indicates that most of the topsoils managed by Houston's are non-sodic (ESP < 6), however Chan (1995) reported that addition of gypsum to a non-sodic sandy soil can also reduce raindrop impact and slaking, which they attributed to the increased electrolyte concentration of the pore water and reduced rate of wetting following immersion.

A number of commercial available products claim to reduce surface crusting, however little research has been conducted for most of these products. For example, phosphoric acid has been reported to increase aggregate stability and total porosity, and reduce soil

crusting (Thein 1976, Ortas & Lal 2012). Polyacrylamides have been reported to significantly increased infiltration rates when sprayed on the surface of crusted soils (Shainberg et al. 1990). Humic acid was suggested to have a significant effect on aggregate stability and this potential to reduce crusting (Piccolo et al. 1997). The humic acid is the fundamental substance acting to promote soil aggregation (Piccolo & Mbagwu 1990, Shephera et al. 2001). Humic acids protect soil aggregates from breakdown by the creation of clay-humic complex over bridging polyvalent cations adsorbed on clay surface (Piccolo & Mbagwu 1994). There are also a range of surfactants, wetters and permeants, which claim to reduce soil crusting by improving infiltration through surface soil.

1.8 Soil hydrological modelling

Despite widespread occurrence of soil crusting and its potential impact on infiltration, irrigation performance, erosion and crop establishment, few crop-soil-climate-hydrological models include routines for simulating the effect of soil crusting on soil water hydrology (Connolly et al. 2002). This is in part due to the scarcity of data that describes the rate and nature of crust formation, and its influence on soil hydrological properties including density, soil water retention, hydraulic conductivity, pore size and pore connectivity. Furthermore, there is little data on how crust formation differs between soil types, soil chemistry and different climates (Nearing et al. 1996, Chahinian et al. 2006). Most existing models simplify the effect of soil crusting by using the simplified United State Department of Agriculture (USDA) curve number approach. The runoff curve is empirical approach developed for predicting the proportion of surface runoff during different rainfall intensity and duration events (Nearing et al. 1996). The runoff curve number approach is however very limited in that only four very

broad soil groups are considered, in which spatial and temporal variability of infiltration are poorly parameterised, or not considered at all (Nearing et al. 1996, Ponce & Hawkins 1996). The only soil-water-climate model we were able to identify that includes a specific soil crust routine is the SWIM2 and SWIM3 models, in which crusting is invoked when surface water ponding develops (Verburg et al. 1996, Huth et al. 2012). Soil crusting is simulated via a surface conductance function, in which an infinitely thin membrane represents the crust. Water flux through the crust is determined by multiplying the surface conductance by the matric potential difference across the crust soil boundary. Simulating soil crusting in one and two dimensional soil-water-climate models (e.g. HYDRUS 2D/4D) would improve the ability to predict the effects of soil crust formation on infiltration, runoff and solute mobilisation over time.

1.9 Thesis objectives

In packet salad production systems, severe crusts have been observed in many soils, following rainfall or irrigation. This crusting has become worse over time due to intensive cultivation, low soil organic matter content and lack of crop residues. Observations indicate that soil crusting has led to reduced infiltration, increased runoff, reduced irrigation efficiency, and as a consequence reduced crop growth and yield. Research in southern Tasmania has shown strong associations between soil crusting and a range of soil physical and chemical properties (Hardie & Cotching 2009). The objectives of this thesis are to (1) investigate the susceptibility of soils to disaggregation and crust formation under intensive irrigated salad production, (2) identify the mechanisms by which soils disaggregate and form crust, (3) determine the consequences of disaggregation and crust formation on soil-water function and crop production, (4) identify soil properties related to aggregate breakdown and crust

formation, (5) test commercially available amendments for reducing aggregate breakdown and crust formation, and (6) improve understanding of the hydrological properties of soil crusts. This thesis comprises five result chapters, three of which have been submitted for publication, which are briefly described as follows:

1.9.1 Chapter 2

The objectives of this chapter were to; (i) evaluate different approaches for measuring aggregate stability, (ii) explore the effects of methodology including different wetting fluids on aggregate breakdown, and (iii) provide guidance on selection of an approach for measuring aggregate stability of soils used by Houston's farms for packet salad production.

1.9.2 Chapter 3

This chapter aimed to (i) explore the role of chemical, physical and mineral properties of soil on aggregate stability, (ii) examine to what extent associations between soil properties and aggregate stability are influenced by the methodology used for measuring aggregate stability, and (iii) identify potential management options to increase aggregate stability.

1.9.3 Chapter 4

This chapter aimed to assess the ability of range of products to reduce soil crusting, and select the potential products for further investigation in the next study (chapter 5).

1.9.4 Chapter 5

This chapter reports: (i) the effectiveness of applying different soil amendments for reducing soil crusting and increasing seedling emergence and crop yield, and (ii) comparison between different approaches for measuring the severity of soil crusting.

1.9.5 Chapter 6

This chapter aims to (i) better understand the effect of crusting on water movement and storage, (ii) determine changes in soil hydrological and physical properties associated with crust developed over time, (iii) collect data to build towards a soil crust model, and (iv) evaluate procedures for parameterizing said model.

General discussion and general conclusion are described in chapter 7 and 8 respectively.

Chapter 2: Evaluation of methods for determining soil aggregate stability

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Abstract

Aggregate stability is widely used as an indicator of soil health and erosion risk, however its use appears to be greatly hindered by a lack of standardised procedures and instrumentation. Aggregate stability can be measured using a number of different approaches each applying different types and levels of disruptive energy, which may or may not adequately match the type and level of disruptive energy experienced by soil aggregates in the field. This paper explores the effects of various approaches for the measurement of aggregate stability, and reports on the mechanisms responsible for the breakdown of an intensively cultivated sandy clay loam and sandy loam in Tasmania, Australia. Aggregate stability was measured by rainfall simulation (RS), wet sieving (WS), ultrasonic vibration (UV) and clay dispersion (CD). Analysis was conducted on 2.00 – 4.75 mm aggregates pre-treated at either (i) air dried moisture content (DRY) or (ii) re-moistened to field capacity at -10 kPa (MOIST). The mechanisms responsible for aggregate breakdown were explored by comparing values of aggregate stability determined using different fluids. Correlations between the various methods for

determining aggregate stability were lower than expected. The highest correlation existed between the DRY – RS and DRY – WS ($R^2 = 0.749$, $P < 0.001$) procedures, whilst some procedures were not significantly correlated at all, especially for aggregates pre-wetted to field capacity. Low correlation between procedures suggests that the mechanisms of aggregate breakdown and thus the type of disruptive energy applied to the aggregates significantly differed between procedures. Efforts to standardise measurement of aggregate stability are not supported as use of a single approach may not adequately predict the behaviour of aggregates in the field. Choice of procedure should aim to mimic the types and levels of disruptive energy experienced by field soils.

2.1 Introduction

The risk or likelihood that soil will undergo breakdown is usually determined by measuring aggregate stability, the ability of soil aggregates, or a size range of aggregates to withstand disaggregation when moistened under the laboratory wetting procedure. Aggregate stability may be determined by a number of procedures, most commonly by: wet sieving (WS), rainfall simulation (RS), and ultrasonic vibration (UV), as well as various measures of dispersion (D). Measurement of aggregate stability has attracted numerous reviews and comparative studies between procedures (Amezketa et al. 1996, Le Bissonnais 1996, Amezketa et al. 2003, Rohoskova & Valla 2004), however guidelines for selection of procedures are lacking.

The selection of an appropriate method or procedure for determining aggregate stability is not straight forward. In theory, selection should be based on the purpose of the analysis, soil type, and the type and level of disruptive energy that soil aggregates experience in the field (Herrick et al. 2001). Ideally the selected procedure would be simple, inexpensive, easily replicated and have high coefficient of variation (COV)

between sites to allow for discrimination between similar soils or treatments, and a low within site COV to reduce the need for replication.

Aggregate stability is commonly determined by wet sieving based on early work of Kemper and Koch (1966) and Kemper and Rosenau (1986). Aggregate breakdown during wet sieving is largely due to slaking and to a lesser extent the physical effects of water movement during lifting of the sieve and abrasion on the sieve surface (Emerson 1967). Slaking results from the compression of air trapped inside aggregates during rapid wetting, as occurs when dry aggregates are rapidly immersed in water (Truman et al. 1990). Slaking by air compression is influenced by the rate of water ingress, which in turn is influenced by soil porosity, pore connectivity, antecedent moisture content and the rate of wetting or immersion (Loch 1994). In soils containing 2:1 clays (vermiculite and smectite), slaking may also result from differential clay swelling (Le Bissonnais 1996, Ben-Hur & Lado 2008, Reichert et al. 2009). Swelling results from thickening of water held on the surface of clay colloids, which cause the clay platelets to be pushed apart. Differential rates of swelling lead to the formation of cracks in the areas of lowest shear strength.

Determination of aggregate stability by wet sieving has been criticised that it does not take into account all mechanisms responsible for aggregate breakdown in the field and tends to overemphasise slaking (Kemper & Rosenau 1986). In response, Le Bissonnais (1996) developed the 'unified framework' that combined use of both water and ethanol as wetting fluids together with slow and fast rates of wetting and mechanical energy (shaking after pre-wetting). By comparing values of aggregate stability, they were able to infer the proportion of aggregate breakdown resulting from different mechanisms. Amezketa (1999) added a further two treatments, in which a salt solution is used to

identify the effect of water quality on aggregate breakdown by dispersion. The unified approach developed by Le Bissonnais (1996) and others is comprehensive and allows for results to be related to processes of aggregate breakdown. However, the procedure is complicated, involves multiple tests and does not appear to be widely adopted by subsequent researchers. Furthermore, both the wet sieving procedures developed by Kemper and Rosenau (1986) and Le Bissonnais (1996) do not consider the effect of raindrop bombardment on disaggregation and are usually conducted over too short a duration to allow for dispersion and flocculation.

Aggregate breakdown by raindrop impact is closely associated with the formation of soil crusts (Awadhwal & Thierstein 1985). When a soil surface is exposed to rainfall, rain drops impact the soil surface causing soil aggregates to shatter into smaller particles. The amount of detachment and shattering generally increases with raindrop size and input energy (Furbish et al. 2007). Fine soil particles are detached and drawn into soil pores by capillary flow, which clog soil pores to form a soil seal or crust (Legout et al. 2005, Bu et al. 2013), resulting in ponding and potentially further aggregate breakdown by slaking (Terry 1992, Gholami et al. 2013).

A number of apparatuses have been developed to measure aggregate stability by rainfall simulation. Ideally rainfall simulation should apply droplets of similar size and level of energy as what aggregates are exposed to in the field. Review of the literature however indicates that a range of droplet sizes, drop heights and rainfall intensity have been used to determine aggregate stability (McCalla 1944, Low 1954, Morin & Benyamini 1977, Norton 1987, An et al. 2012).

Field aggregates may also break down by dispersion, especially if they contain sodic clays. Dispersion tends to occur over longer durations than most procedures used to

measure aggregate stability and thus its importance may be underestimated by wet sieving and rainfall simulation tests. Dispersion is influenced by many factors including; (i) clay charge characteristics, (ii) cation ratios, especially the exchangeable sodium percentage (ESP), (iii) the electrolyte concentration of infiltration water (Emerson 1967, Agassi et al. 1981, Agassi et al. 1985, Römkens et al. 1990, Le Bissonnais 1996, Marchuk et al. 2012), and (iv) attractive forces between colloidal particles (Emerson 1967, Sumner 1992). Clay dispersion may be measured using qualitative (Emerson 2002) or quantitative tests in which the amount of turbidity or suspended clay is compared between different fluids, dispersion test or levels of agitation (Rengasamy et al. 1984), as well as procedures that measure erosion such as the pinhole test (AS 1289.3.8.3 1997).

In addition to wet sieving, rainfall simulation and clay dispersion, sonication or ultrasonic vibration have been used to measure aggregate stability (Imeson & Vis 1984, Mentler et al. 2004, Fristensky & Grismer 2008, Zhu et al. 2009, Rawlins et al. 2013). Sonication creates cavitation, the formation of an empty space or bubbles within soil aggregates and water. As these bubbles expand they rupture the soil along cracks and lines of weakness, leading to cleavage of aggregates into smaller fragments or primary particles. Whilst sonication is a very effective means of disaggregating soils, the procedure is not representative of the behaviour of field soils.

This study was conducted to; (i) explore effects of methodology on values of aggregate stability, (ii) estimate the effects of different wetting fluids on aggregate breakdown, and (iii) provide guidance on selection of methodology and procedures for the determination of aggregate stability of intensively cultivated sandy clay loam soils.

2.2 Material and methods

2.2.1 Field site

The study was conducted on sandy loam and sandy clay loam top soil from six farms for packet salad production in the Coal Valley, southern Tasmania, Australia (42° 44' 00", 147° 26' 00"). Climate is described as cool temperate with 500 mm annual rainfall, yearly temperature and rainfall are presented in Figure 2.1 (Bureau of Meteorology 2014). Samples were collected from 20 sites, stratified to include soils derived from six different geological materials including; Quaternary and Pleistocene alluvial fans, Triassic sandstone, Tertiary basalt, Tertiary – Quaternary sediments, and Tertiary - Quaternary alluvial deposits. Soil texture was fairly consistent between sites, with 18 of the 20 sites having sandy clay loams, and two sites having sandy loams.

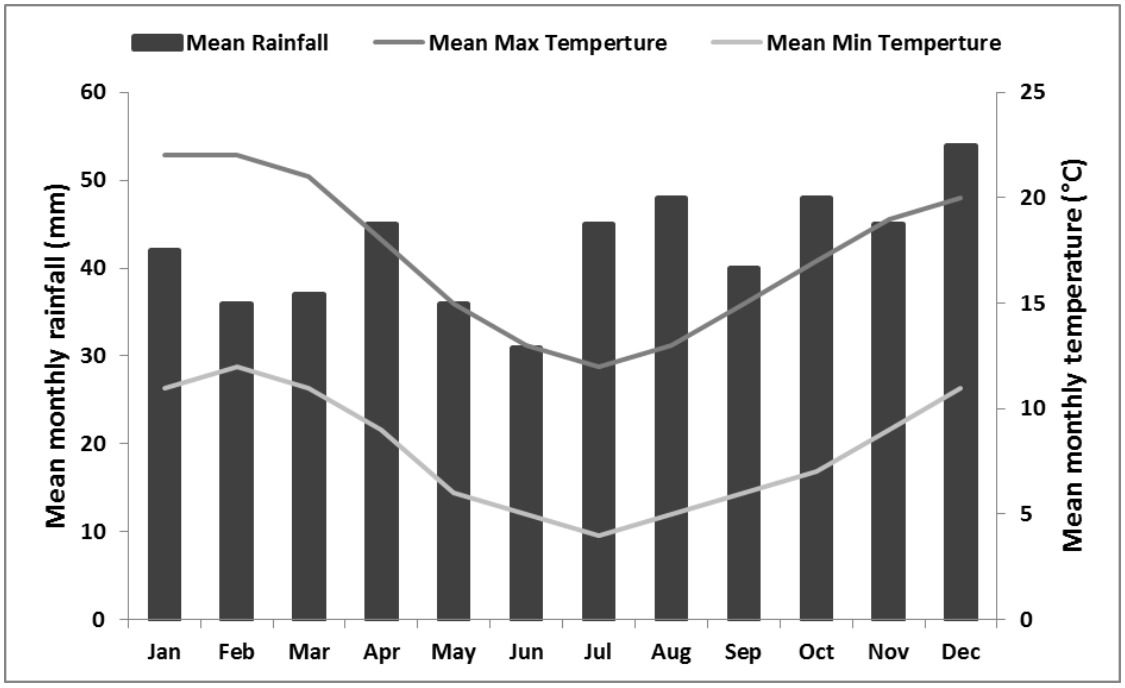

Figure 2.1. Monthly rainfall and temperature at Richmond, Coal Valley, Tasmania, Australia.

2.2.2 Soil sampling and range of soil properties

At each site, approximately 2000 g of soil was collected using a small hand shovel from the crop bed at 0 – 5 cm depth, within six hours after tillage and bed formation and prior to rainfall or irrigation. Samples were collected in triplicate from 20 sites (60 samples), in which replicates were located 10 to 15 m apart. Soil aggregates were placed in plastic containers for transport to the laboratory. Gravimetric moisture content at the time of sampling was determined for each site by drying duplicate samples at 105^{o} C for 24 hours. All soils were air dried at 40^{o}C for 24 hours, then carefully hand sieved to separate out the 2.00 – 4.75 mm size fraction of which around 1000 g was obtained. The 2.00 – 4.75 mm size fraction was selected for investigation as it is considered to be the desired soil aggregate size range for production of packet salad.

The 2.00 – 4.75 mm aggregate fraction was dominated by quartz (43 – 73%) and smectite or smectite-kaolinite (8 – 30%). Sand content ranged from 56 to 70%, clay content ranged from 16 to 33 %, and silt content ranged from 8 to 15%. The mean of SOC of the 60 samples was 2.1 % (range, 1.45 to 3.87 %) while the mean hot water extractable carbon was 78.7 mg/l (range, 52.5 to 117.1 mg/l). Exchangeable Ca^{2+} ranged from 6.1 to 26.8 meq/100g, exchangeable Mg^{2+} ranged from 2.3 to 15.3 meq/100g, exchangeable K^{+} ranged from 0.66 to 1.65 meq/100g and exchangeable Na^{+} ranged from 0.13 to 1.35 meq/100g.

2.2.3 Determination of aggregate stability

Prior to analysis, aggregates were pre-treated at two moisture contents, (i) air dried by oven drying at 40 ^{o}C for 24 hours (DRY), (ii) field capacity (MOIST) by allowing aggregates to equilibrate at -10 kPa on a micro glass bead tension table over a period of one week (Cresswell 2002). Aggregate stability of both the DRY and the MOIST

aggregates was determined by wet sieving (WS), rainfall simulation (RS) and ultrasonic vibration (UV). Clay dispersion was determined on dry aggregates only. For each method, the same amount of soil aggregates was used for DRY and MOIST analysis.

Aggregate stability was determined on the 2.00 – 4.75 mm aggregate fraction for each of the three replicates. Aggregate stability was determined by wet sieving (WS) using an Eijkelkamp wet sieving apparatus, in which 4 g of aggregates were slowly immersed in distilled water and mechanically raised and lowered for three minutes (oscillation speed was 36 cycles per minute) on top of a 250 μm sieve. Aggregate stability was determined as the proportion of aggregates retained on the sieve after removing of coarse particles by ultrasonic disruption and re-sieving.

Aggregate stability was also determined by rainfall simulation (RS) using a Cornell sprinkle infiltrometer. Approximately 30 g of air dry 2.00 – 4.75 mm aggregates was placed on the top of 250 μm sieve (200 mm diameter size) mounted within a large funnel containing a 380 mm diameter filter paper (manufacture code 415) to catch the < 250 μm particles as they passed through the sieve. Tap water (EC = 70 μs /cm) was applied from the Cornell infiltrometer from 1.84 m height, at 0.7 kPa head, from 130 needles over a 314 cm^2 area, at a constant rate of 36 mm/hr, for four minutes. The mean weight diameter MWD of the droplets determined by the flour pellet method was 3.09 ± 0.14 mm (Laws and Parsons 1943). The proportion of aggregates dislodged from the sieve surface by rainfall impact was ignored. Aggregate stability was determined as the proportion of aggregates retained on the sieve after removing of coarse particles by ultrasonic disruption and re-sieving.

Disaggregation by ultrasonic vibration (UV) was conducted using a Branson sonic vibration generator with a 60 mm long, 16 mm diameter probe operated at sufficient

energy to just initiate cavitation. Four grams of oven dried aggregates were placed in a 75 ml beaker, slowly immersed in distilled water and exposed to ultrasonic vibration for five seconds. Aggregate stability was determined as the weight of remaining aggregates > 250 μm, after removing the coarse fraction by further ultrasonic dispersion and re-sieving.

Clay dispersion was measured following the spontaneous dispersion method by Rengasamy et al. (1984), in which 20 g of soil aggregates were weighed into a 120 ml transparent jar. Then, 100 ml distilled water was slowly added down the sides of the jar, the solution shaken end-over-end at 30 rpm for one hour, and left for four hours to settle. The amount of suspended clay was determined by extracting a 10 ml aliquot of the suspension extracted from a depth of 5 cm and drying at 105 ^{o}C.

2.2.4 Wetting fluids

The effect of different wetting fluids on DRY aggregate stability was investigated for two sandy clay loam soils classifying as Tertiary – Quaternary sediments origin to represent poorly aggregated soil and a soil at average aggregate stability. WS was conducted with (i) distilled water, (ii) irrigation water (EC=450 μS/cm), to better represent field conditions, (iii) 0.02 M $CaCl_2$ solution to reduce dispersion, (iv) 5 % sodium hexametaphosphate to examine near complete dispersion, and (v) kerosene to restrict clay swelling and dispersion during suspension. Analysis was also conducted by RS with distilled water, 0.02 M $CaCl_2$, 5 % sodium hexametaphosphate and irrigation water to explore the effects of different fluids on aggregate breakdown by raindrop impact. The procedures for WS and RS with these fluids are the same as described in Chapter 2.3.

2.2.5 Statistical analysis

Correlation between methods of measuring aggregate stability was explored by using Spearman correlation for all 60 samples that were collected from 20 sites. The ability of three procedures (RS, WS, UV) to discern differences in aggregate stability between sites was explored by analysis of the within and between site Coefficient of Variation (COV). A lower within site COV indicated analytical precision while higher between sites COV favours the ability to discriminate between sites, methods and / or treatments. The significant differences in aggregate stability between procedures were determined using T-test in SPSS (version 21).

2.3 Results

2.3.1 Comparison between methods

The stability of DRY aggregates was significantly less than MOIST aggregates for all procedures (Figure 2.2). For DRY aggregates, values of aggregate stability were significantly greater for UV than WS, which were also significantly higher than RS. For MOIST aggregates values of aggregate stability were significantly higher for WS than the other two procedures.

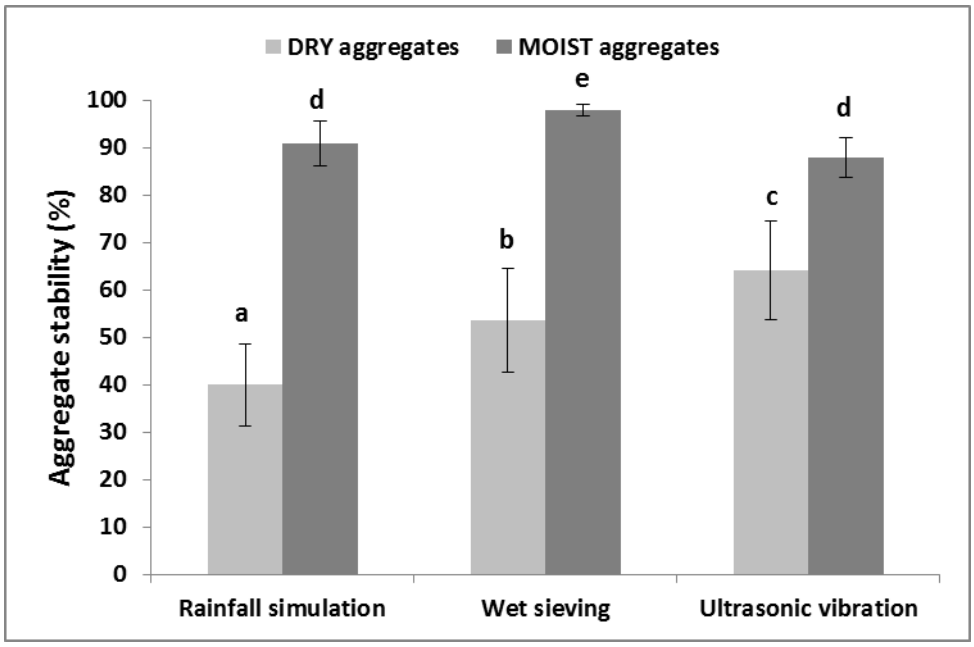

Figure 2.2. Average soil aggregate stability at air dried moisture and field capacity (kPa) determined by rainfall simulation, wet sieving and ultrasonic vibration. Error bars represent ± 1 standard deviation.

The within site COV was lower for MOIST aggregates (COV = 0.5 - 2.8), than dry aggregates (COV = 5.3 – 6.1), while the between site COV was lower for MOIST (COV = 1.1- 4.9) than DRY aggregates (COV = 15.5 – 21.1) (Table 2.1). The most precise method (lowest within site COV) was the MOIST – WS procedure while the least precise method was DRY – RS. However, the DRY – RS had the greatest ability to discriminate between sites, while the MOIST – WS procedure had the least ability to discriminate between sites.

Table 2.1. Influence of methods and moisture pre-treatment on aggregate stability.

Initial soil moisture	Methods	Mean aggregate stability %	Std. deviation	Average within site COV %	Average between sites
Air dried	Rainfall simulation	39.93	8.44	6.1	21.1
(DRY)	Wet sieving	53.63	10.79	5.3	20.1
	Ultrasonic vibration	64.18	9.98	5.6	15.5
Field	Rainfall simulation	90.82	4.49	2.1	4.9
capacity	Wet sieving	97.85	1.08	0.5	1.1
(MOIST)	Ultrasonic vibration	87.92	3.57	2.8	4.0

Correlations are presented between the different methods for the same pre-treatment moisture in Table 2.2. The correlation between different procedures conducted on DRY aggregates was higher than those conducted on MOIST aggregates (Table 2.2). For DRY aggregates, the highest correlation between procedures existed between RS and WS ($R^2 = 0.74$, $P < 0.001$), and RS and UV ($R^2 = 0.62$, $P < 0.001$) while for MOIST aggregates the only significant correlation was between RS and UV ($R^2 = 0.31$, $P < 0.05$). Clay dispersion (D – DRY) was significantly correlated with aggregate stability determined by DRY – WS but not DRY – RS or DRY – UV.

Table 2.2. Spearman correlation between different measures of aggregate stability and antecedent moisture content.

Comparison between methods			Moisture pre-treatment			
			DRY		MOIST	
			R^2	P value	R^2	P value
Rainfall simulation	*vs*	Wet sieving	0.74	<0.001	0.17	0.190
Rainfall simulation	*vs*	Ultrasonic vibration	0.62	<0.001	0.31	<0.05
Rainfall simulation	*vs*	Clay dispersion	0.04	0.738		
Wet sieving	*vs*	Ultrasonic vibration	0.40	<0.001	0.18	0.170
Wet sieving	*vs*	Clay dispersion	0.39	<0.001		
Ultrasonic vibration	*vs*	Clay dispersion	0.10	0.472		

Blank cells were due to clay dispersion only being conducted on DRY aggregates.

2.3.2 Effect of different fluids on aggregate stability

The type of wetting fluid significantly influenced values of aggregate stability for both RS and WS procedures (Figure 2.3). The highest value of aggregate stability occurred for WS with kerosene while the lowest value occurred for RS with 5 % sodium hexametaphosphate. No significant differences existed between values of aggregate stability determined by distilled water, and irrigation water for both methods (WS, RS), whilst wet sieving with 0.02 M $CaCl_2$ resulted in significantly higher values of aggregate stability than when measured in distilled water.

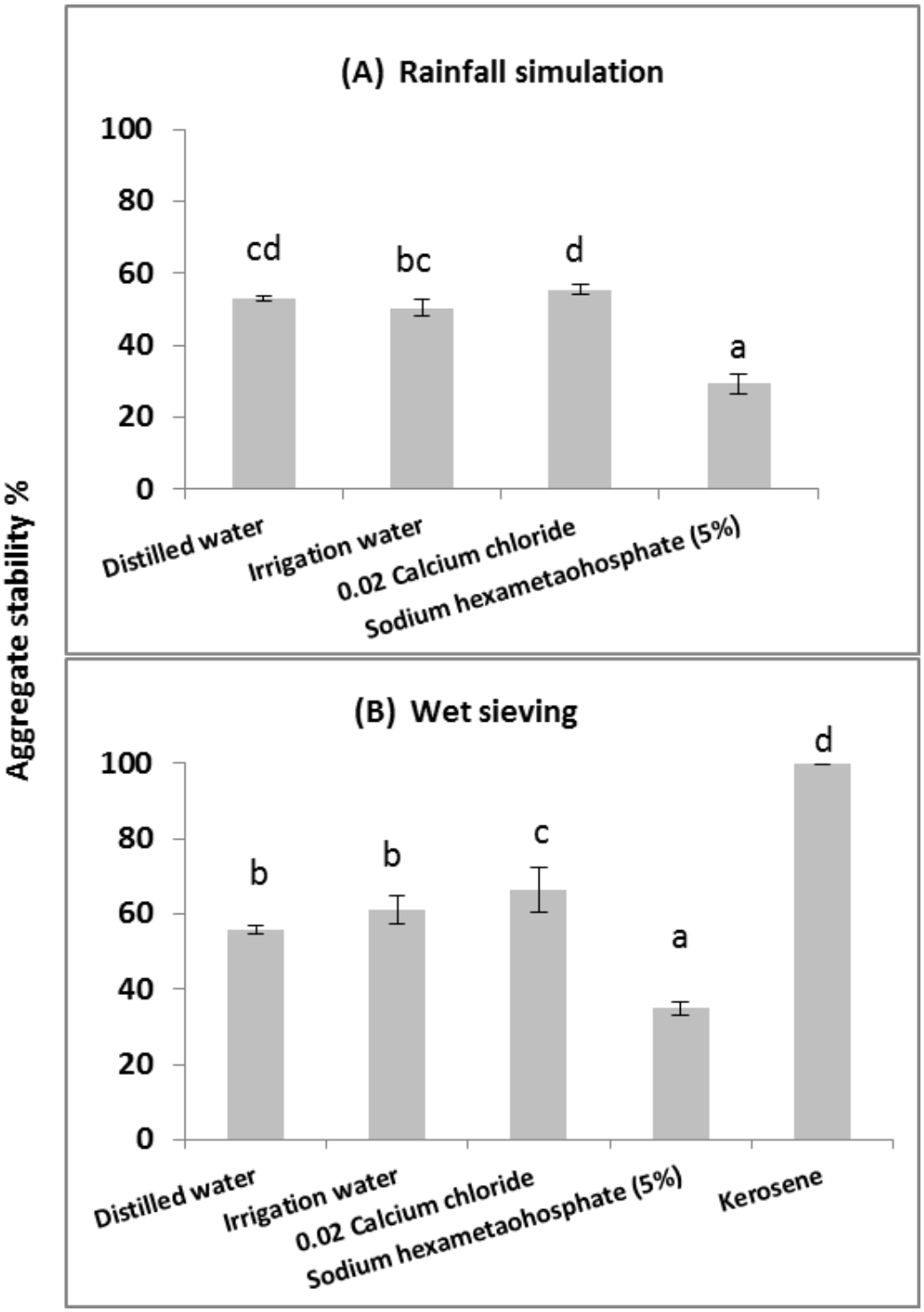

Table 2.3. Effect of different fluids on DRY aggregate stability determined by (a) rainfall simulation and (b) wet sieving. Error bars indicate ± standard deviation.

2.4 Discussion

2.4.1 Aggregate breakdown during wet sieving

The relative importance of slaking by differential swelling is known to be strongly influenced by soil moisture content, soil particle size and clay mineral type (Concaret 1967, Emerson 1967, Emerson & Chi 1977, Kemper et al. 1985). For example, in soil dominated by smectite, aggregate breakdown results from clay platelets pushing apart from each other and the formation of cracks in the area of lowest shear strength (Yoder 1936).

Comparison between different moisture pre-treatments and fluids indicates that when DRY aggregates were sieved in water, aggregate breakdown principally resulted from differential clay swelling, followed by dispersion with only minor contribution from air entrapment and mechanical abrasion. Pre-wetting aggregates to field capacity increased their stability relative to that of air dried aggregates, despite physical softening of the moistened aggregates. The lower stability of the air dried aggregates was attributed to increased slaking (Le Bissonnais 1996, Leelamanie et al. 2013), in which moisture content prior to immersion influenced the rate of water entry into the aggregate, and thus degree of air compression. When DRY aggregates were rapidly immersed in water, water entered the aggregates due to both gravitational and capillary flow.

For the MOIST aggregates, the reduced matric potential gradient within the aggregates, and presence of pre-existing soil water decreased the rate of capillary flow into the aggregates. As aggregates immersed in kerosene are not subject to swelling, the difference in aggregate stability (DRY – WS) between distilled water (55%) and kerosene (99 %) indicates that around 44% of the breakdown of the DRY aggregates during immersion in water was due to swelling, whilst approximately 1 % of breakdown

was due to air compression alone. This approach may underestimate slaking by air compression as it does not account for differences in the density and surface tension between kerosene and water that would affect their ingress into aggregates. For pre-moist aggregates, in which air compression is minimal and swelling has already taken place, aggregate stability in distilled water averaged 98 %, with the 2% loss in aggregate stability attributed to abrasion during movement in the water column or the sieve surface. In contrast, comparison between the DRY – WS procedure in distilled water (55%) to that of 0.02 M $CaCl_2$ solution (66%) indicates that dispersion reduced aggregate stability by 11 %.

Comparison of aggregate stability values between fluids was able to infer the relative important of the different breakdown mechanisms during laboratory immersion. However, the extent to which the same mechanisms contributed to aggregate breakdown in the field is uncertain, especially as wet sieving does not replicate rainfall impact and the test duration was too short to adequately allow for dispersion and flocculation.

2.4.2 Aggregate breakdown during rainfall simulation

Comparison between tests (RS, WS, UV) demonstrates that raindrop impact is an important mechanism for initiating aggregate breakdown due to the mechanical energy of the impacting raindrops, which neither the WS or UV procedures simulate. It has been widely reported that raindrop impact is the dominant mechanism of aggregate breakdown in field soils (Jimba & Lowery 2010). Yet raindrop impact is not simulated in wet sieving procedures and therefore underestimated. For example, mean values of DRY aggregate stability for all sites determined by RS were approximately 14 % lower than values determined by WS (Figure 2.2). For Dry – WS, aggregate stability in 0.02 M $CaCl_2$ was 66 % compared with 55 % by DRY – RS in 0.02 M $CaCl_2$. Thus in the

absence of dispersion, it appears that the additional energy associated with raindrop impact with RS method resulted in approximately 10 – 14 % more aggregate breakdown (Figure 2.3).

In the field, aggregate breakdown under rainfall and /or irrigation results from a combination of raindrop impact, air compression, differential swelling and dispersion. Raindrop impact is the primary source of energy that initiates the detachment of soil particles, and also has the capacity to separate soil material arising from the underlying surface (An et al. 2012). Determining the relative contribution of rain drop energy compared to that of slaking and / or dispersion is however difficult. The energy associated with raindrop impact occurs simultaneously with rapid soil wetting, which act together to produce more aggregate breakdown than raindrop impact or aggregate immersion alone. The extent to which differential clay swelling contributed to aggregate breakdown during RS was not tested as Kerosene could not be applied through the Cornell infiltrometer. Consequently, the contribution to aggregate breakdown via raindrop impact as opposed to slaking by clay swelling could not be ascertained. In the absence of air compression and swelling (i.e. when soil moisture is near field capacity) it is assumed that raindrop impact was the major mechanism responsible for aggregate breakdown. Jimba and Lowery (2010) also reported that soil aggregates subject to rainfall are more likely to disaggregate from direct raindrop impact than by slaking during wetting and thus slaking is considered to be a secondary process (Tanaka et al. 1997).

In the field, reduction in infiltration rate following blockage of soil pores by disaggregated soil particles usually results in ponding and run-off on the soil surface. Consequently, mechanisms such as clay swelling, air entrapment, and dispersion are

facilitated by immersion in water, which in turn is likely to be influenced by the depth, duration and rate at which ponding forms. Further research is required to better understand the contribution that *in situ* ponding, micro-relief and crust formation contribute to secondary disaggregation processes during rainfall and/ or irrigation events.

2.4.3 Selection of methods for determining aggregate stability

Selection of an appropriate procedure and moisture pre-treatment for determining aggregate stability is not straight forward. It was expected the three methods (which all measure aggregate stability) would be highly correlated, however R^2 values between procedures were below 0.75, and no significant correlation existed for two of the three procedures for MOIST aggregates. Poor correlation implies that researchers cannot assume all procedures to be similar, and no single procedure is an adequate means of determining aggregate stability.

Poor correlation between procedures is likely to have resulted from the application of different types and levels of disruptive energy, which favour aggregate breakdown by different mechanisms or combination of mechanisms. Consequently, selection of procedures to measure aggregate stability need to consider the type of disruptive forces and breakdown processes to which field aggregates are subjected. Analysis of the within and between sites COV indicated the MOIST – WS to be the most precise or repeatable approach, however its ability to discriminate between sites was less than that of all other techniques. Ability to determine differences in aggregate stability between sites or treatments was greatest for the DRY – RS and the DRY – WS approaches although these procedures came at a cost of reduced precision.

Selection of an appropriate method for determining aggregate stability needs to not only consider within and between site variability, but also the types of disruptive energy and dominant mechanisms of aggregate breakdown to which field aggregates are exposed. As no one method adequately simulated the range of disaggregation mechanisms experienced by aggregates in the field, consideration should be given to determining aggregate stability using multiple procedures and multiple moisture pre-treatments to maximise the discrimination between sites and or treatments. If resources prevent use of more than one method, we recommended that aggregates exposed to rainfall and or overhead irrigation be assessed using the RS approach. Whereas, aggregates exposed to sudden immersion such as during flood or furrow irrigation are considered to be best measured using WS. Ideally all analysis should be conducted using aggregates at moisture contents similar to those prior to irrigation or rainfall, or as a default, air dried moisture content. In order to reveal differences between sites and or treatments, the amount of disruptive energy applied to the aggregates (usually the duration of the test) should aim to achieve between 40 – 60% of breakdown of aggregates.

2.5 Conclusion

No single method of measuring aggregate stability is suitable for all soils and conditions. Furthermore, no procedure for measuring aggregate stability adequately mimics the types and levels of disruptive energy that field soils experience. In this study, breakdown of dry sandy clay loam aggregates principally resulted from raindrop impact and slaking by differential swelling, and to a lesser extent clay dispersion. Slaking by air compression and abrasion / movement through the water column were minor processes. Analysis of the within and between COV indicated that DRY – RS and DRY – WS had the greatest capacity to discriminate variance in aggregate stability between

sites. However, the moderate to poor correlation between methods demonstrated that each method applied a different combination of breakdown mechanisms, which favoured breakdown of some aggregates and to a lesser extent others. Furthermore, initial soil moisture content influenced the relative importance of different breakdown mechanisms, specifically slaking by air compression and differential clay swelling.

Efforts to standardise assessment of aggregate stability are not supported, rather researchers should consider use of multiple methods and moisture pre-treatments, with adjustment of test duration to achieve 40 – 60% aggregate breakdown in order to discriminate between sites / treatments. If a single test is to be selected it is considered the DRY – RS method better represents disaggregation processes when aggregates are exposed to rainfall or overhead irrigation, while the WS method may better represent aggregates exposed to floods or furrow irrigation.

Next chapter

Chapter 2 revealed that aggregate stability greatly varied between sites (28 – 73 % WS-DRY) despite all sites being subjected to similar management. This variance in aggregate stability is applied to explore which soil properties were associated with aggregation at the Houston's sites with aims of identifying management options for improving aggregation.

Chapter 3: Influence of soil properties on the aggregate stability of cultivated sandy clay loam soils

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Abstract

Frequent cultivation and overhead irrigation has led to severe surface crusting, erosion and poor irrigation performance on sandy clay loam soils in the Coal River Valley, Tasmania, Australia. This study was established to identify the key soil properties related to aggregate breakdown and options for reducing soil crusting. Soil aggregates were collected from 0 – 5 cm depth from 20 sites managed for packet salad and lettuce production. Aggregate stability of air dried 2.00 – 4.75 mm aggregates was determined by rainfall simulation, wet sieving and clay dispersion. Soil aggregates were analysed for; particle size, mineralogy, soluble and exchangeable cations, pH, EC, labile carbon and total carbon. The association between aggregate stability and the measured soil properties was explored using Spearman correlation, linear regression, and regression tree analysis. Aggregate stability determined by rainfall simulation was closely associated with soil properties that promote aggregation including, ECEC and the proportion of polyvalent cations (Ca^{2+}, Al^{3+}). In contrast, aggregate stability determined by wet sieving was associated with soil properties that promote disaggregation, including: quartz and sand content, and to lesser extent the proportion of monovalent cations (especially K^{+}). Clay dispersion was closely associated with pH, quartz content,

soil texture and the sodium adsorption ratio. Soil carbon appeared to have only moderate influence on aggregate stability, but not clay dispersion, while labile carbon was not significantly related to any measure of aggregate stability or clay dispersion. Similarly, the proportion of Na^+ ions was not related to either measure of aggregate stability and only moderately related to clay dispersion. Options for improving aggregate stability appear limited as aggregate stability was strongly related to the content of inherent soil properties such as sand/quartz and smectite content. However, the moderate-high correlation between exchangeable Ca^{2+} and aggregate stability indicates that soil crusting may be reduced through application of products that are rich in Ca^{2+} such as gypsum.

Keywords Aggregate breakdown • Inherent soil properties • Rainfall simulation • Soil crusting • Wet sieving• Crusting.

3.1 Introduction

Decline in soil structure is commonly associated with decreased aggregate stability following loss of soil carbon. Aggregate stability is a measure of the ability of soil aggregates to withstand breakdown to small fragments when quickly moistened. Aggregate stability is commonly related to soil properties including; organic carbon, texture, clay mineralogy and the proportion of monovalent verses polyvalent cations. Factors responsible for soil aggregation are understood to be size dependent (Tisdall & Oades 1982, Oades & Waters 1991). Soil organic carbon or fractions of carbon such as labile carbon and biologically active carbon are strongly associated with the stability of macro aggregates (Tisdall & Oades 1982). In contrast, particle size, mineralogy, cation ratios and cementing agents are strongly associated with the stability of micro

aggregates (Tisdall & Oades 1982, Chenu et al. 2000, Duchicela et al. 2012, Portella et al. 2012).

Sand content has been reported to have negative influence on aggregate stability (Idowu 2003), and vice-versa for clay content (Fernandez-Ugalde et al. 2013). Sands tend to have low aggregate stability due to their large particle size and low surface area compared with clays that have high surface area and negatively charged surfaces, which readily bond together via metal cations or organic molecules (Bazzoffi et al. 1995). Different types of clay minerals influence aggregate stability, due in large part to differences in surface area, charge of clay platelets, and swelling behaviour (Chenu & Guerif 1991, Wakindiki & Ben-Hur 2002, Lado & Ben-Hur 2004, Fernandez-Ugalde et al. 2013). For example, smectitic clays are more dispersive than kaolinitic clays (Singer 1994), due to the large internal surface area of smectite compared with kaolinite.

Aggregate breakdown by dispersion is influenced by the proportion of monovalent verses polyvalent cations on the exchange complex, which is commonly expressed by ratios such as exchangeable sodium percentage (ESP) (Shainberg & Letey 1984, Amezketa & Aragues 1995a). Traditionally these measures have focused on the proportion of Na^+ relative to other cations due to sodium's large hydrated radius and low electronegativity (Laurenson et al. 2011). Although K^+ has smaller hydration radius than that of Na^+, in low CEC soils, presence of moderate levels of K^+ may also result in dispersion (Auerswald et al. 1996, Igwe & Okebalama 2006). In recent years, cation ratios have been developed to incorporate the dispersive potential of K^+ including; the exchangeable potassium percentage (EPP), exchangeable cation ratio (ECR), monovalent cations adsorption ratio (MCAR) and the cation ratio of soil structural stability' (CROSS) (Rengasamy & Marchuk 2011, Marchuk et al. 2014). Presence of

polyvalent cations (Fe^{3+}, Al^{3+}, Ca^{2+}, Mg^{2+}) commonly act as flocculating agents promoting soil aggregation (Six et al. 2000, Igwe et al. 2009). Baohua and Doner (1993) reported that soils with a low concentration of polyvalent cations are more susceptible to dispersion because of the repulsion between the negatively charged clay particles. Polyvalent cations may act together with clay or organic matter to further strengthen soil aggregates (Chan & Heenan 1999, Wuddivira & Camps-Roach 2007).

Aggregate stability may be influenced by soil management, often in association with changes in organic carbon content. Intensively cultivated soils are particularly prone to loss of carbon by, (i) erosion following tillage and irrigation, (ii) oxidation, especially the use of powered implements that lift and throw soil into the air, (iii) mechanical breakdown due to the impact of tillage implements, and (iv) limited input of crop residues, due to above ground biomass being harvested, bailed for stock feed or directly grazed (Elliott 1986, Ross 1993, Six et al. 2000).

Measurement of aggregate stability has not been standardised. Le Bissonnais (1996) demonstrated that soils differed in their susceptibility to aggregate breakdown depending on the type of aggregate stability test as each type of test applied different forms and levels of disruptive energy. Aggregate stability is usually measured by wet sieving, which involves raising and lowering aggregates above a sieve or sieves whilst immersed in water. Consequently, wet sieving emphases aggregate breakdown via slaking and dispersion. However, soil crusting and disaggregation of field soils are in large part due to raindrop impact (Roth & Eggert 1994), which is not replicated in wet sieving tests. Consequently, understanding and predicting aggregate breakdown may require use of multiple forms of analysis.

The intensive management practices at Houston's farms in Southern Tasmania have led to loss of soil organic carbon, soil structure decline and surface crusting, which have reduced infiltration of rainfall and irrigation causing runoff, erosion, and poor irrigation performance (Hardie et al. 2013). Observations between different soils across the five Houston's farms demonstrate considerable differences in the degree of soil crusting despite all blocks having similar management practices. Production of packet salad requires very high levels of cultivation, prolonged fallows and considerable irrigation. On a yearly basis, soils are cropped 2 – 3 times a year, resulting in 6 – 12 cultivations with a rotary hoe annually, with an average of 2.5 ML/ha per year of irrigation. Additional vehicle traffic also occurs during sowing, spraying for weeds and pests and harvesting. This study was established to (i) explore the role of specific soil attributes, or combination of attributes on aggregate stability (ii) examine to what extent associations between soil properties and aggregate stability were influenced by methodology for measuring aggregate stability and (iii) identify management options to increase aggregate stability.

3.2 Materials and methods

3.2.1 Field sites

As described in Chapter 2.2.1, this study was conducted on farms located in the lower Coal Valley, southern Tasmania, Australia (42^{o} 44' 00", 147^{o} 26' 00"). The Coal Valley has a cool temperate climate with 500 mm annual rainfall, yearly temperature and rainfall range are presented in the Figure 3.1 (Bureau of Meteorology 2014). Sampling was conducted at 20 sites distributed across five properties used by Houston's Farms for packet salad production. Sample sites were stratified to include top-soils developed on six different Cainozoic geological units, largely Tertiary and Quaternary sediments. Top

soil texture was fairly consistent between sites, with 18 of the 20 sites having sandy clay loams, and two sites having sandy loams.

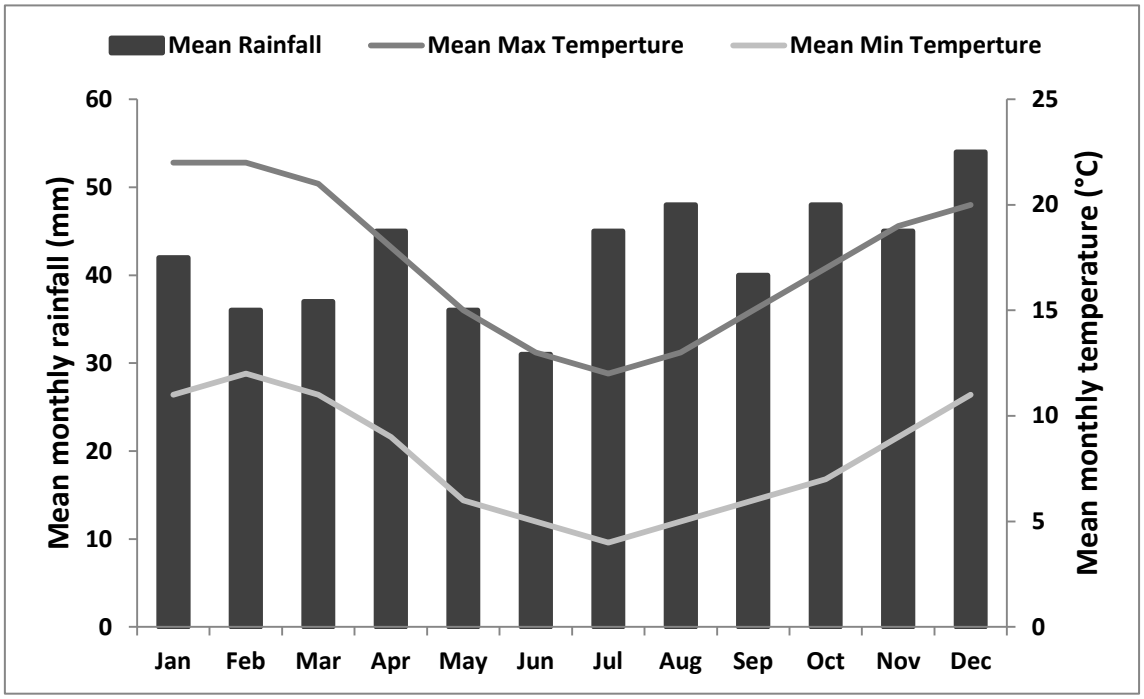


Figure 3.1. Monthly rainfall and temperature at Richmond, Coal Valley, Tasmania, Australia.

3.2.2 Soil sampling and preparation

Further details are presented in Chapter 2.2.2. At each site, approximately 2000 g of soil aggregates was collected from the crop bed of 0 – 5 cm depth within six hours after tillage and bed formation and prior to rainfall or irrigation, using a small hand shovel. Samples were collected in triplicate, in which replicates were located 10 to 15 m apart. Soil aggregates were placed in plastic containers for transport to the laboratory. Gravimetric moisture content at the time of sampling was determined for each site by drying duplicate samples at 105^{o} C for 24 hours. All soils were air dried at 40^{o}C for 24 hours, then carefully hand sieved to separate out the 2.00 – 4.75 mm size fraction of which around 1000 g was obtained. The 2.00 – 4.75 mm size fraction was selected for

investigation as it is considered to be the desired aggregate size range for production of packet salad.

3.2.3 Measures of aggregate stability

As described in Chapter 2.2.3, aggregate stability was determined on the 2.00 – 4.75 mm aggregate fraction for each of the three replicates. Aggregate stability was determined by wet sieving (WS) using an Eijkelkamp wet sieving apparatus, in which 4 g of aggregates were slowly immersed in distilled water and mechanically raised and lowered for three minutes (oscillation speed was 36 cycles per minute) on top of a 250 μm sieve. Aggregate stability was determined as the proportion of aggregates retained on the sieve after removing of coarse particles by ultrasonic disruption and re-sieving.

Aggregate stability was also determined by rainfall simulation (RS) using a Cornell sprinkle infiltrometer. Approximately 30 g of air dry 2.00 – 4.75 mm aggregates was placed on the top of 250 μm sieve (200 mm diameter size) mounted within a large funnel containing a 380 mm diameter filter paper (code 415) to catch the < 250 μm particles as they passed through the sieve. Tap water (EC = 70 μs /cm) was applied from the Cornell infiltrometer from 1.84 m height, at 0.7 kPa head, from 130 needles over a 314 cm^2 area, at a constant rate of 36 mm/hr for four minutes. The mean weight diameter MWD of the droplets was determined by the flour pellet method to be 3.09 ± 0.14 mm (Laws and Parsons 1943). The proportion of aggregates dislodged from the sieve surface by rainfall impact was ignored. Aggregate stability was determined as the proportion of aggregates retained on the sieve after removing coarse particles by ultrasonic disruption and re-sieving.

Clay dispersion was measured following the spontaneous dispersion method by Rengasamy et al. (1984), in which 20 g of soil aggregates were weighed into a 120 ml

transparent jar, 100 ml distilled water was slowly added down the sides of the jar, then shaken end-over-end at 30 rpm for one hour, and left for 4 hours to settle. The amount of suspended clay was determined by extracting a 10 ml aliquot of the suspension extracted from a depth of 5 cm and drying at 105 ^{o}C.

3.2.4 Chemical, physical and mineral analysis

Chemical and physical analyses were conducted on the 2.00 – 4.75 mm soil aggregate fraction for each of the three replicates for each site. Soil organic carbon (SOC) was determined by wet oxidation by CSBP laboratories (Walkley & Black 1934). Labile carbon was measured by both cold and hot water extraction as described by Ghani et al. (2003), in which 3 g of air dry aggregates were placed in a 50 ml polypropylene centrifuge tube with 30 ml of distilled water, which was shaken end-over-end at 30 rpm for 30 minutes, then centrifuged at 3500 rpm for 20 minutes for determination of cold water extracted carbon. The supernatant was then filtered through a 0.45 μm cellulose nitrate membrane. The remaining sediment was resuspended in 30 ml of distilled water and placed in a hot-water bath for 16 hours at 80 ^{o}C. The sediment was re-suspended then centrifuged and the supernatant extracted through a 0.45 μm cellulose nitrate membrane filter to determine the hot water extracted carbon (HWC). Total organic and inorganic carbon for both hot and cold water extracted supernatants was measured in duplicate using a Shimadzu total organic carbon analyser.

Selected soil chemical properties were determined for the 2.00 – 4.75 mm aggregates by CSBP laboratories according to Rayment and Lyons (2011). Electrical conductivity and soil pH in water was measured using a soil to solution ratio of 1:5, and pH in $CaCl_2$ was measured after adding calcium chloride solution to soil solution (4A1, 4B3, 3A1). Soluble and exchangeable cations were determined by using a soil solution ratio of 1:5

(5A4, 15E1). The exchangeable acidity Al^{+3} and H^{+} were measured by titration with NaOH and HPWl following extraction with 1M KCl in a 1:5 ratio for one hour (15 G1). Calcium carbonate percentage was determined by using dilute hydrochloric acid (19B2). Reactive Al^{3+} and Fe^{3+} were determined by Tamms reagent (oxalic acid/ammonium oxalate). CEC was measured as the effective cation exchangeable capacity (ECEC) as the sum of cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} and Al^{3+}). Sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), exchangeable potassium percentage (EPP), the cation ratio of soil structural stability (CROSS), ECR (exchangeable cation ratio) and monovalent cations adsorption ratio (MCAR) were calculated according to Rengasamy and Marchuk (2011) and Marchuk et al. (2014).

As particle size and clay mineralogy tend not to vary greatly over short distance, a single bulked sample from all three replicates (30 m apart) was used for analysis of particle size and clay mineralogy at each site. Particle size of the 2.00 – 4.75 mm soil aggregate fraction was measured by mid infrared (MIR) by CSBP (Rayment & Lyons 2011). Clay mineralogy was determined by the Mineral Resources Tasmania using an automated Philips X-Ray diffractometer system using nickel-filtered copper radiation at 40kV/30mA and a sample spinning proportional detector.

3.2.5 Statistical analyses

A number of statistical procedures were used to explore the relationships between soil chemical, physical and mineralogical properties vs aggregate stability and clay dispersion. These included (i) Spearman correlation in SPSS (version 21), (ii) forward linear regression in SAS Enterprise guide version 6.1 and (iii) regression tree analysis in JMP 10. The use of all three statistical procedures was desired to overcome assumptions and limitations associated with each type of analysis, differences in normality between

soil attributes, the large number of soil attributes, and interest in creating a flow diagram based model of what influences aggregate stability for farmers.

The regression tree analysis was conducted as an alternative data-analysis method to nonlinear regression in which values are partitioned into smaller groups, where the interactions are explicit. Partition analysis recursively partitions data to form a tree of decision rules until the desired fit is reached (SAS-Institute 2014). Decision trees were constructed manually, where splits were required to exceed a minimum logworth value of 2.0 ($p = 0.01$). Results are presented for significantly (logworth>2.0) related properties. Spearman correlation and regression tree included all soil properties, whilst linear regression included only the correlated soil properties identified by the Spearman correlation in which clay and exchangeable Al^{3+} were excluded to prevent analysis of dependant variables i.e. sand, silt and clay.

3.3 Results

3.3.1 Aggregate stability and clay dispersion verses soil properties (Spearman correlation)

The influence of soil properties on dry aggregate stability varied between both the methods used for measuring aggregate stability, and each of the three statistical procedures. The 2.00 – 4.75 mm aggregate fraction was dominated by quartz (43 – 73%) and smectite or smectite-kaolinite (8 – 30%). Sand content ranged from 56 to 70%, clay content ranged from 16 to 33 %, and silt content ranged from 8 to 15%. The mean of SOC of the 60 samples was 2.10 %, which ranged from 1.45 to 3.87 %, while the mean hot water extractable carbon was 78.7 mg/l, which ranged from 52.5 to 117.1 mg/l. Exchangeable Ca^{2+} ranged from 6.1 to 26.8 meq/100g, exchangeable Mg^{2+} ranged from

2.3 to 15.3 meq/100g, exchangeable K^+ ranged from 0.66 to 1.65 meq/100g and exchangeable Na^+ ranged from 0.13 to 1.35 meq/100g.

Aggregate stability determined by RS and WS were both significantly correlated with the proportion of quartz, smectite, sand and silt (Table 3.1). The highest correlated soil property was smectite content for aggregate stability determined by RS, compared with quartz content for aggregate stability determined by WS. Neither measure of aggregate stability was significantly correlated with clay content. Aggregate stability determined by RS and WS were both significantly correlated with SOC determined by wet oxidation, which had a R^2 of 0.46 and 0.59 respectively. Clay dispersion was significantly correlated with the proportion of quartz, sand and clay respectively (Table 3.1), but unlike the other two measures of aggregate stability, clay dispersion was not significantly related to smectite content or any measure of soil carbon.

For other soil properties, aggregate stability (RS, WS) was highly correlated with ECEC, followed by exchangeable Ca^+, exchangeable Mg^{2+}, EPP, ECR and MCAR (Table 3.1). Exchangeable sodium appeared to have little to no influence on aggregate stability as either Na^+ or SAR were correlated to any measure of aggregate stability while ESP and CROSS were the lowest ranked soil properties to be significantly correlated with aggregate stability (RS). Aggregate stability determined by RS was significantly correlated with pH, but no correlation existed between pH and aggregate stability determined by WS. Aggregate stability (RS+WS) was not significantly related to any of the soluble cations.

Correlation between aggregate stability determined by clay dispersion and soil properties was notably different to aggregate stability determined by RS and WS. Clay dispersion was highly correlated with pH, then a range of similarly correlated variables

including Ca^{2+}, Na^{+}, SAR, ESP, CROSS and ECR (Table 3.1). No correlation existed between clay dispersion and exchangeable Mg^{+2}, K^{+}, ECEC, EPP, MCAR or soluble cations.

Table 3.1. Correlation between aggregate stability determined by rainfall simulation, wet sieving and clay dispersion versus soil properties.

Variables	Aggregate stability methods		
	Rainfall simulation	Wet sieving	Clay dispersion
Quartz %	-0.43**	-0.71**	-0.50**
Smectite	0.62**	0.34**	
Clay %			0.40**
Sand %	-0.31*	-0.40**	-0.41**
Silt %	0.58**	0.35**	
SOC %	0.46**	0.59**	
HTC(mg/l)		0.30*	
Ca^{2} (meq/100g)	0.76**	0.45**	-0.32*
Mg^{2+} (meq/100g)	0.61**	0.42**	
Na^{+} (meq/100g)			0.27*
ECEC (meq/100)	0.81**	0.52**	
SAR (mmol/L)			0.35**
ESP %	-0.33*		0.34**
CROSS (mmol/L)	-0.34**		0.32*
EPP %	-0.71**	-0.50**	
MCAR (mmol/L)	-0.46**	-0.31*	
ECR (mmol/L)	-0.66**	-0.38**	0.32*
pH ($CaCl_2$)	0.45**		0.53**
Reactive Al^{3+} (mg/kg)	0.64**	0.60**	

* = significance P < 0.05, ** = significance P < 0.001, – negative relationship, blank cells not significantly correlated.

3.3.2 Soil properties vs aggregate stability (linear regression)

3.3.2.1 *Rainfall simulation (RS)*

Linear regression demonstrated that 70 % of variability in aggregate stability could be explained by exchangeable Ca^{2+} (Table 3.2). The content of sand and quartz, organic carbon (wet oxidation) and silt explained only between 1 – 9 % of the variance in aggregate stability. No correlation existed between aggregate stability (RS) and cation ratios such as SAR, EPP and CROSS or organic carbon determined by hot water extraction.

Table 3.2. Forward linear regression between aggregate stability (rainfall simulation) and soil properties.

Variable Entered	Partial R-Square	Model R-Square	C(p)	F Value	Pr > F
Exch. Ca^{2+} (meq/100g)	0.70	0.70	175.93	133.26	<.0001
Sand %	0.09	0.79	112.00	22.64	<.0001
Quartz %	0.07	0.86	59.36	27.48	<.0001
Organic carbon%	0.02	0.88	50.96	5.67	0.0208
Silt %	0.01	0.89	45.48	4.53	0.0425

Only the significant correlations are shown

3.3.2.2 *Wet sieving (WS)*

The relationship between aggregate stability determined by WS and soil properties differed substantially to that determined by RS. Around 46 % of the variance in aggregate stability (WS) was explained by quartz content, 18 % by sand content, while 11% was explained by exchangeable Ca^{2+} (Table 3.3). Smectite content and organic carbon (wet oxidation) explained between 2 – 4 % of variance in aggregate stability (WS). Aggregate stability (WS) was not significantly related to SAR, CROSS or ESP.

Table 3.3. Forward linear regression between aggregate stability (wet sieving) and soil properties.

Variable	Partial R-Square	Model R-Square	C(p)	F Value	Pr > F
Quartz %	0.46	0.46	95.80	49.86	<.0001
Sand %	0.18	0.64	47.56	28.20	<.0001
Exch. Ca^{2+}	0.11	0.75	17.79	25.49	<.0001
Smectite %	0.04	0.79	8.52	10.59	0.002
Organic carbon %	0.02	0.81	4.46	6.24	0.016

Only the significant correlations are shown

3.3.2.3 *Clay dispersion*

Clay dispersion was significantly related to pH ($CaCl_2$), quartz and sand contents, exchangeable Na^+, reactive Al^{3+}, ESP and ECEC (Table 3.4). Around 45 % of the variance in clay dispersion was explained by pH, whilst 13 % was explained by quartz content. Other related soil properties explained only 2 – 5 % of variance in clay dispersion. Clay dispersion was not linearly related to soil organic carbon or soluble cations.

Table 3.4. Forward linear regression between clay dispersion and soil properties.

Variable	Partial R-Square	Model R-Square	C(p)	F Value	Pr > F
pH Level ($CaCl_2$)	0.45	0.45	64.18	47.24	<.0001
Quartz %	0.13	0.58	36.83	18.42	<.0001
Sand %	0.05	0.63	28.64	7.07	0.0102
Exch. Na^+	0.04	0.67	21.73	6.84	0.0115
Reactive Al^{3+}	0.04	0.71	15.87	6.64	0.0127
ESP %	0.03	0.74	11.35	6.03	0.0174
ECEC (meq/100g)	0.02	0.76	8.00	5.35	0.0247

Only the significant correlations are shown

3.3.3 Soil properties related to aggregate stability (RS, WS) and clay dispersion according to regression tree analysis

Results from the regression tree analysis were influenced by methodology used to measure aggregate stability. Decision tree analysis indicated that aggregate stability determined by RS was most closely associated with ECEC. ECEC values less than 28 meq/100g were then most closely related to reactive Al^{3+} followed by smectite and then ESP for soils that had reactive Al^{3+} less than 858 mg/kg, or EPP when reactive Al^{3+} was more than 858 mg/kg (Figure 3.2). When ECEC was greater than 28 meq/100g, aggregate stability determined by RS was most closely related to exchangeable Ca^{2+}.

Decision tree analysis indicated aggregate stability determined by WS was most closely related to quartz content, followed by MCAR (quartz > 0.73) and silt (quartz <0.73) as shown in Figure 3.3. When MCAR was greater than 0.45, aggregate stability determined by WS was influenced by sand and by reactive Al^{3+} (sand < 66), then by ESP (reactive Al^{3+} > 783).

Clay dispersion was most closely associated with pH ($CaCl_2$), followed by quartz content, then silt content when pH was less than 6.5 (Figure 3.4). SAR contributed to dispersion when pH was greater than 6.5.

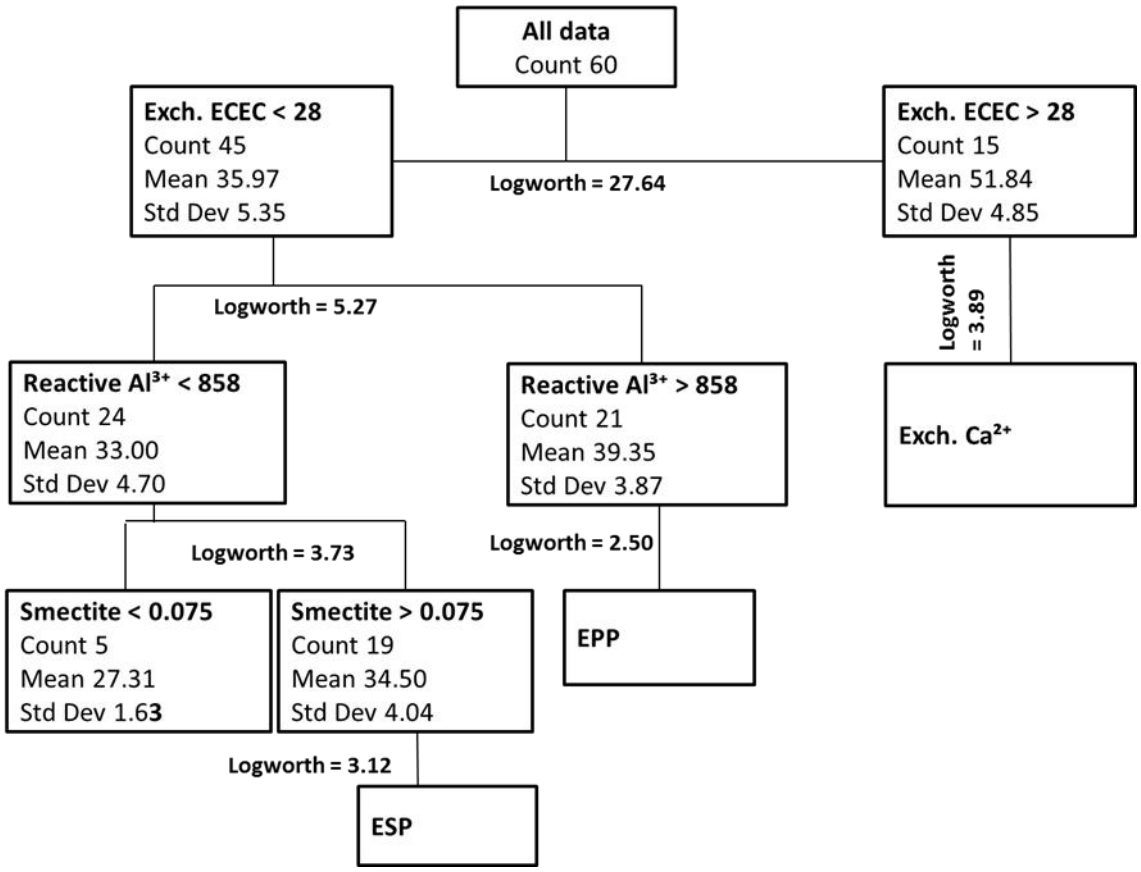


Figure 3.2. Decision tree analysis of the influence of soil properties on aggregate stability determined by rainfall simulation (logworth>2 = P < 0.01).

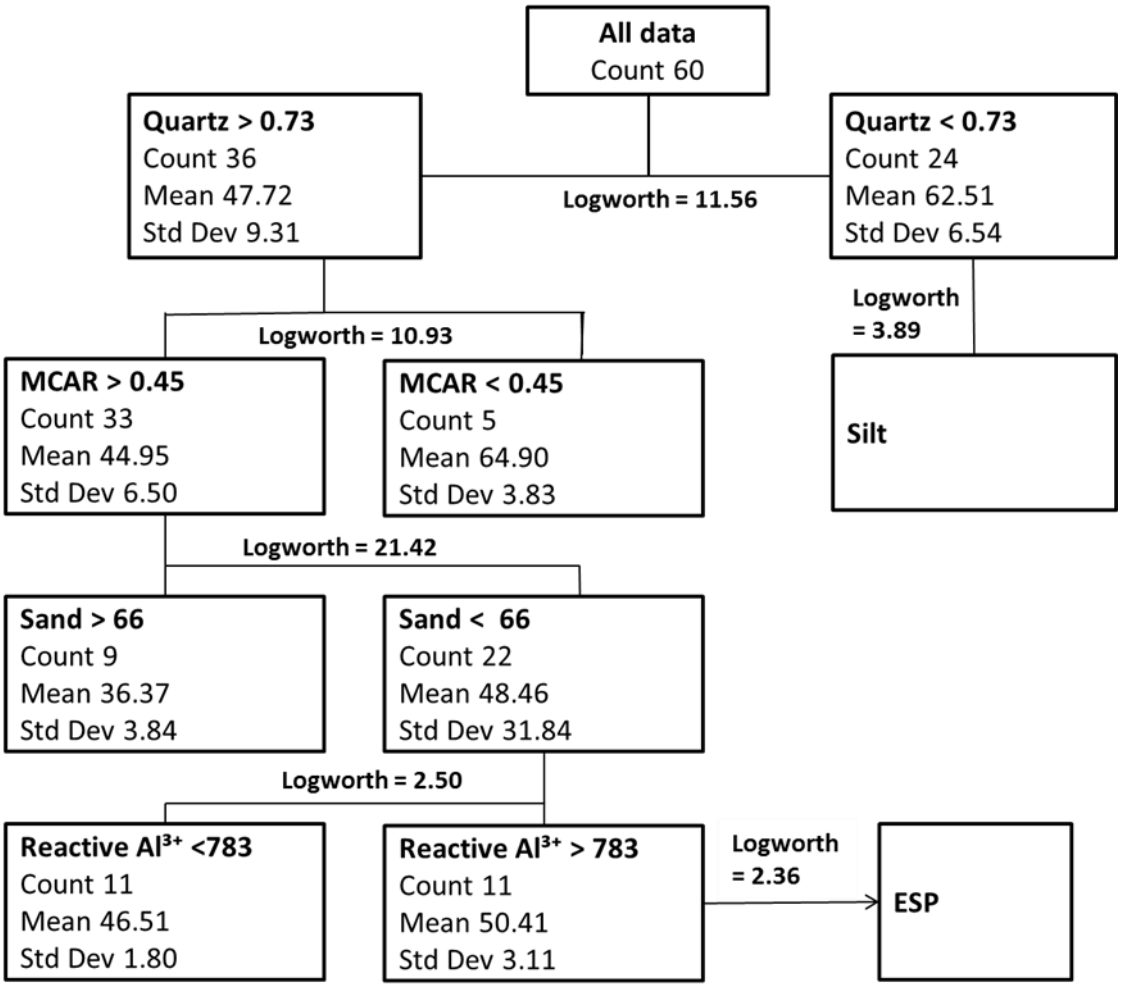


Figure 3.3. Decision tree analysis of the influence of soil properties on aggregate stability determined by wet sieving (logworth>2 = P < 0.01).

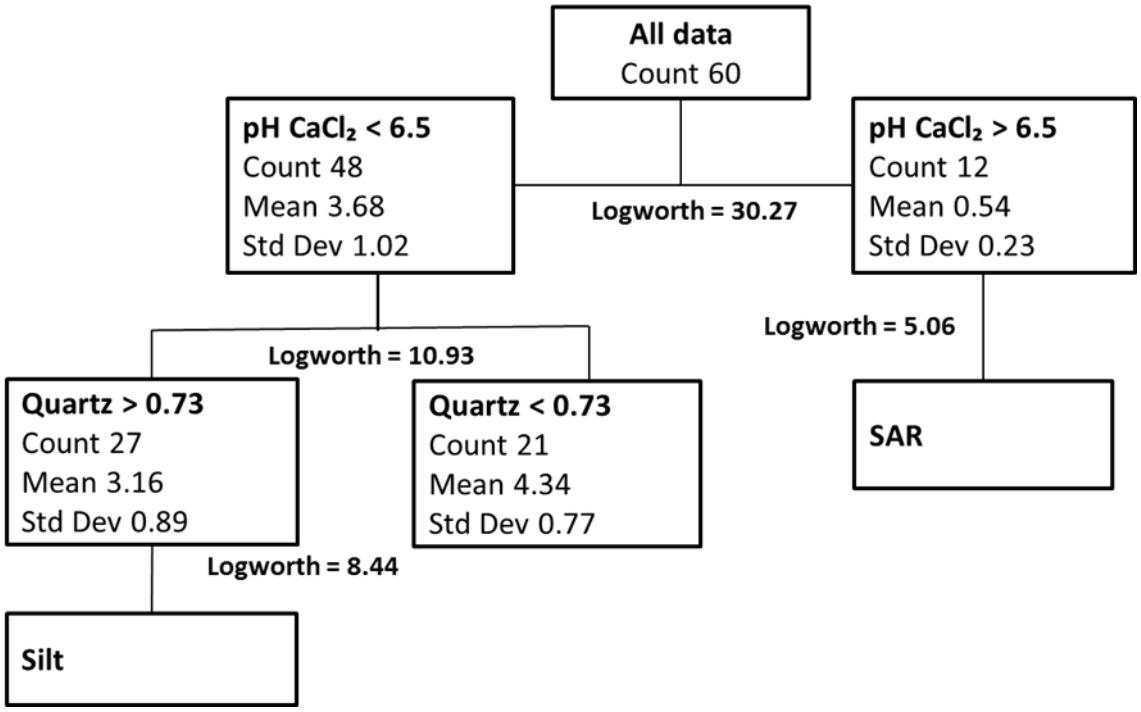


Figure 3.4. Decision tree analysis of the influence of soil properties on aggregate stability determined clay dispersion (logworth>2 = P < 0.01).

3.3.4 Summary of analysis: The top-ranked five soil properties related to aggregate stability

No single soil property was consistently related to all three measures of aggregate stability, and all three statistical procedures. Soil properties associated with aggregate stability differed considerably between the three measures of aggregate stability, whereas within each measure of aggregate stability, the three statistical procedures tended to identify similar soil properties. Overall, the soil properties most commonly related to aggregate stability were, quartz content, followed by exchangeable Ca^{2+}, then sand content, smectite content, pH, then ECEC (Table 3.5). For RS, aggregate stability had the highest association with ECEC, exchangeable Ca^{2+} and then to a lesser extent EPP and smectite content. For WS, aggregate stability had the highest association with quartz content and then to a lesser extent exchangeable Ca^{2+}, sand content and organic carbon. Aggregate stability determined by clay dispersion was most closely related to pH, then quartz content and then to a lesser extent sand content and SAR. Soil

properties that were either not ranked or infrequently ranked in the five most related soil properties with aggregate stability (RS+WS) and clay dispersion include, ESP, CROSS, exchangeable Mg^{2+} and labile carbon (all not listed), ECR, MCAR, (both listed once), SAR and clay content (both listed only twice).

Table 3.5. The top-ranked soil properties to be significantly related to aggregate stability by analysis type.

Aggregate stability methods	Spearman correlation		Linear regression		Regression tree	
	properties	R^2	properties	R^2	properties	Logworth
Rainfall simulation	ECEC (meq/100g)	0.81	Exch. Ca^{2+}	0.70	ECEC (meq/100g)	27.64
	Exch.Ca^{2+}	0.76	Sand %	0.09	Reactive. Al^{3+}	5.27
	EPP %	-0.71	Quartz %	0.07	Exch.Ca^{2+}	3.89
	ECR (mmol/L)	-0.66	Organic carbon %	0.02	Smectite %	3.72
	Smectite %	0.62	Silt %	0.01	EPP %	2.50
Wet sieving	Quartz %	-0.71	Quartz	0.46	Quartz %	11.56
	Organic carbon %	0.59	Sand %	0.18	MCAR (mmol/L)	10.93
	ECEC (meq/100g)	0.52	Exch. Ca^{2+}	0.11	Silt %	3.89
	EPP %	-0.50	Smectite %	0.04	Sand %	21.42
	Exch. Ca^{2+}	0.45	Organic carbon %	0.02	Reactive Al^{3+}	2.50
Clay dispersion	pH ($CaCl_2$)	-0.54	pH ($CaCl_2$)	0.45	pH ($CaCl_2$)	30.27
	Quartz %	-0.50	Quartz %	0.14	Quartz %	6.05
	Sand %	-0.41	Sand %	0.05	SAR (mmol/L)	5.06
	Clay %	-0.40	Exch. Na^{+}	0.04	Silt %	8.44
	SAR (mmol/L)	-0.35	Reactive Al^{3+}	0.04	NS	

NS = not significant, order indicates relative degree of association.

3.4 Discussion

The type of soil properties associated with aggregate stability differed among the three methods. Aggregate stability determined by RS was related to soil properties associated with aggregation, namely ECEC and the proportion of polyvalent cations (Ca^{2+}, Al^{3+}), whilst aggregate stability determined by WS was more closely related to soil properties associated with disaggregation, namely sand and quartz content and to a lesser extent

the proportion of monovalent cations (MCAR, EPP) and organic carbon. Clay dispersion was related to factors active in re-aggregation and flocculation, namely pH, quartz content and different measures of particle size.

These differences emphasise that the importance of soil properties to stability/instability of soil aggregates vary according to the method used to measure aggregate stability as also reported by Haynes (1993) and Le Bissonnais (1996). For RS, aggregates were bombarded with water that rapidly drained through the sieve such that disaggregation mostly resulted from raindrop impact and thus mechanical failure of the aggregates rather than slaking or dispersion. For WS in which the aggregates were immersed and moved through a column of water such that disaggregation resulted from slaking by differential swelling and air compression, and to a lesser extent dispersion. Disaggregation during the clay dispersion test also involved slaking and dispersion, but was also followed by a period of settling which allowed for flocculation.

Overall, aggregate stability determined by RS was positively related to ECEC, the proportion of polyvalent cations, and to a lesser extent the presence of smectite (Table 3.5). The strength of the association with ECEC was unexpected, which was attributed to ECEC being comprised of 60 % Ca^{2+}. Positively charged cations Ca^{+2} and Al^{+3} help bond negatively charged soil clay particles into more stable micro aggregates (Chan & Heenan 1999, Igwe et al. 2009). This is due to polyvalent cations having greater charge density than monovalent cations, resulting in flocculation (Six et al. 1999, Wuddivira & Camps-Roach 2007). Numerous studies have shown aggregate stability increases with Ca^{2+}, and thus the use of gypsum for promoting aggregate stability and preventing dispersion (Hanay et al. 2004, Bennett et al. 2014).

Previous studies have reported that aggregate stability is negatively related to smectite content due to these clays facilitating swelling, which occurs in soils with high ESP and low electrolyte concentration (Stern et al. 1991, Singer 1994, Reichert et al. 2009). In our study, the presence of smectite increased rather than decreased aggregate stability (RS, WS), which we attributed to the high sand content of the soil. Presence of any clay, but especially the large external surface area of smectite increased opportunity for primary particles to bond into aggregates.

Aggregate stability determined by WS was negatively related to quartz and sand content (Table 3.5), which is consistent with other studies (Kemper & Koch 1966, Chaney & Swift 1984). This is due to the large size and low surface area of sand particles, and because sand does not have negative charges like clay that are easily held together by aggregating agents such as metal cations or organic molecules (Bazzoffi et al. 1995).

Studies have shown that aggregate stability is negatively related to various cation ratios such as SAR, ESP, CROSS and ECR (Laurenson et al. 2011, Rengasamy & Marchuk 2011), especially when disaggregation occurs by differential swelling or dispersion. In this study, aggregate stability determined by RS and WS was negatively correlated with EPP, ECR and MCAR. These cation ratios indicated that exchangeable K^+ in addition to Na^+, contributed to aggregate breakdown. Exchangeable K^+ was found to be as, if not more important than exchangeable Na^+ for disaggregation of these soils. Disaggregation due to K^+ has been shown by Laurenson et al. (2011) in soil with low exchangeable Na^+ and high exchangeable K^+. Other studies also report that soil aggregates exposed to rainfall or overhead irrigation, undergo breakdown due to high exchangeable K^+ (Levy & Feigenbaum 1996, Rengasamy 2010).

Results demonstrate that clay dispersion was highly correlated with pH and quartz content, and to lesser extent SAR and clay content (Table 3.5). All statistical tests ranked pH as the most closely associated parameter with clay dispersion. Voelkner et al. (2015) also reported that clay dispersion was negatively correlated with pH. The relationship between clay dispersion and pH was attributed to Al^{3+} becoming more available at low pH (soil pH ranged from 4.4 to 7.4) and thus active in flocculation, while at higher pH, Na^{+} and K^{+} were likely to become available and aid in dispersion. According to the decision tree analysis and Spearman correlation, SAR was significantly related to clay dispersion whilst abundance of Na^{+} was linearly related to clay dispersion. However, associations with Na^{+} were generally less important than the influence of pH and particle size on dispersion.

Unexpectedly, SOC was not consistently or strongly associated with aggregate stability. SOC was correlated with aggregate stability determined by rainfall simulation (R^2 = 0.46) and wet sieving (R^2 = 59), but not clay dispersion. However, linear regression indicated that only 2 % of the variance in aggregate stability determined by RS was explained by SOC. Furthermore, labile carbon was only indicated by Spearman correlation to be moderately correlated with aggregate stability determined by WS and not related to any measure of aggregate stability when analysed by linear regression or decision trees. Overall, SOC was moderately and inconsistently associated with aggregate stability determined by RS and WS while labile carbon was poorly associated with aggregate stability determined by WS. This finding is in contrast to the extensive literature that strongly relates aggregate stability to SOC, or measures of labile carbon (Tisdall & Oades 1982, Chenu et al. 2000, Loveland & Webb 2003).

In most soils, aggregate stability is known to be directly related to soil carbon content, whilst in some soils this relationship has been shown to be threshold dependent (Ahmad & Roblin 1971, Carter 1992). Therefore, organic carbon content needs to be exceeded before a relationship between aggregate stability and SOC is established. For example, Boix-Fayos et al. (2001) showed that a threshold of 3 – 3.5 % SOC had to be attained to achieve increases in aggregate stability, and then no effects on aggregate stability were observed in soils below this threshold.

We postulate the lack of a relationship between labile carbon and aggregate stability determined by RS, and the poor to moderate relationship between SOC and aggregate stability determined by RS and WS was due to the soil carbon levels at most sites being below or near a soil carbon-aggregate stability threshold, in which the extent of carbon lost by cultivation may have been great. Consequently, the remaining soil carbon is recalcitrant and no longer makes a substantial contribution to aggregate stability. Further research is required to have better understanding the nature of the recalcitrant carbon and its potential role in aggregation.

3.5 Conclusions

Aggregate stability was found to be related to different soil properties depending on the means by which aggregate stability was determined and to a lesser extent, the type of statistical analysis. Overall, RS demonstrated aggregate stability was related to soil properties that promote aggregation and flocculation such as $Ca^{2+}$and ECEC, whilst WS demonstrated aggregate stability was related to soil properties that promote disaggregation and dispersion including sand, quartz content and to lesser extent the proportion of monovalent cations. Clay dispersion was closely related to pH possibly as a surrogate for Al^{3+} at low pH and Na^{+} at high pH. Curiously, aggregate stability

determined by RS and WS was only moderately correlated with SOC, however neither measure of aggregate stability (RS, WS) nor clay dispersion were closely associated with labile carbon or the abundance/proportion of Na^+. For aggregate stability determined by RS and WS, the amount of K^+ appeared to be as important if not more important than the amount Na^+ in promoting disaggregation.

Management options for improving aggregation appear limited as aggregate stability was mostly related to inherent soil properties such as sand/quartz and smectite content. However, the positive relationship between aggregate stability determined by RS and polyvalent cations such as exchangeable Ca^{2+} and Al^{3+} may provide some opportunity to improve aggregate stability through application of products that are rich in Ca^{2+} such as gypsum or Al^{3+} such as alum. We found limited evidence that aggregate stability determine by RS and WS was influenced by total carbon or labile carbon, as such it is likely that remaining carbon in these soils is recalcitrant and not actively involved in aggregation. However, this does not preclude the addition of new carbon to promote aggregation. Field trials are required to determine if application of compost, manure or crop residues to supply or enable production of organic compounds that do promote aggregation.

Next chapter

Based on the results in Chapter 3, a number of Ca^{+2} and carbon based products together with a range of commercially available products are explored in a preliminary study in Chapter 4. The potential of these products to reduce soil crusting in field condition was assessed by measuring different physical and chemical properties of soil over time.

Chapter 4: Evaluation of physical and chemical soil amendments for reducing soil crusting

Abstract

This preliminary study assessed a range of commercially available soil amendments for preventing or reducing soil crusting on intensively cultivated sandy clay loam soil used for packet salad production. Twelve treatments were replicated three times included phosphoric acid (PA), infiltrax (IX), thiocal (TL), humic acid (HA), surface gypsum (SG), penterra (PN), phosphoric acid with thiocal, clay, incorporated gypsum (IG), wire mesh (WM), incorporated paper waste (IPW) and surface paper waste (SPW). The severity and likelihood of crusting was estimated based on measurement of; aggregate stability, infiltration rate, crust density and penetration resistance, which were measured 8 and 42 days after treatment application. Results show that none of the treatments prevented soil crusting, however some treatments (IPW, IG, SPW, SG and WM) significantly reduced the severity of soil crusting relative to the control. In addition, application of PA and PT significantly increased infiltration rate and reduced crust density at day 8, but not day 42. No other amendments were observed to have influenced crust severity. The paper waste and gypsum treatments were the most effective for reducing crust severity at both sampling dates, while the phosphoric acid was shown to be effective only at day 8. These products were included in a replicated experiment that assessed the effect of rate of different treatments on the amelioration of surface crusting presented in Chapter 5.

4.1 Introduction

Soil crusting is a global issue, which results in increased runoff and erosion, and reduced crop production due to poor water infiltration and seedling emergence. Despite its impact on the environment and agricultural production, the management of soil crusting has received relatively little research effort. Review of the literature indicates potential to manage soil crusting through increased carbon content via application plant residues or organic wastes, and improved electrolyte balance usually through application of gypsum. The ability of compost and gypsum to ameliorate soil crusting has been widely reported (Dormaar 1983, Chaney & Swift 1984, Hanay & Yardimci 1992, Haynes 2000, Rasse et al. 2000). However, there are a number of alternative commercially available products, which claim to reduce soil crusting yet have limited or no scientific evaluation. These include soil surfactants or wetting agents that are reported to increase water infiltration (Song et al. 2014). Treating soils with humic acid has been suggested to improve aggregate stability, as the humic substances have the ability to penetrate between clay particles and displace cemented agents with weaker bonded clay particles (Piccolo et al. 1997). Other product such as liquid fertilizers (thiocal) that contains sulphur and calcium has not received sufficient evaluation. A small number of studies also indicate that application of phosphoric acid may reduce soil crusting (Robbins et al. 1972, Ghani et al. 2003, Moore et al. 2011).

The aim of this chapter is to (i) assess the ability of range of products to reduce soil crusting and (ii) select the potential effective products for further investigation in the next study (Chapter 5).

4.2 Material and methods

4.2.1 Site description and treatment application

This experiment was conducted at Houston's farm, which is located in the Coal River Valley in southern Tasmania, Australia (42.72532^{o} South, 147.43182^{o} East). The farm is exposed to intensive cultivation to produce leafy packet salad mixes. The climate is defined as cool moderate with 500 mm of annual rainfall (Bureau of Meteorology 2015). Yearly mean maximum temperature ranges from 12 – 22 ^{o}C and mean minimum temperature range of 4 – 12 ^{o}C.

A randomised complete block design plot was established with three replications per treatment. The experiment contained four beds, each was 1.2 m wide and 55 m long, each bed contained 11 plots, 3 m long with a 2 m gap between plots. In total, there were 6 control plots and 38 treatment plots. Beds remained in fallow over the duration of the experiment to maximise the effect of raindrop impact on soil crusting, and to facilitate measurement of soil crusting.

Treatments included both physical and chemical ameliorants including 22 % phosphoric acid (75 ml/m^{2}), infiltrax (20 ml/m$^{2)}$, thiocal (1 ml/m^{2}), humic acid (2.9 ml/m^{2}), surface applied gypsum (0.5 kg/m^{2}), penterra (0.467 ml/m^{2}), phosphoric acid & thiocal, subsoil clay (13 kg/m^{2}), incorporated gypsum (0.5 kg/m^{2}), incorporated paper waste (8 kg/m^{2}) and surface paper waste (3 kg/m^{2}). The humic acid included gypsum (0.5 mls), humus (0.3 mls), vitazyme (0.1 mls) and molasses (2 mls). The paper waste was sourced from Skog paper mill as an organic amendment. The composition of the paper waste and gypsum is presented in Table 4.1. Infiltrax is a non –toxic biodegradable liquid product that contains a combination of electrolytes wetters and specific functional groups that are reported to aid in the aggregation and stabilisation of soil aggregates (Michael 2013).

Thiocal is a liquid fertiliser that contains sulphur and calcium that has been reported by the manufacturer to increase soil aggregation through provision of available Ca^{2+} (Campbells 2011). Penterra as a soil wetting agent has been reported to have the ability to prevent soils from locking up, improve soil structure and increase water movement by reducing the surface tension between the water and the soil (Geoponics 2016).

Paper waste, gypsum and sub-surface clay were applied by hand to the soil surface directly after tillage, then incorporated to a depth of 5 – 7 cm using a rotary hoe. After incorporation, other soil amendments were applied to the soil surface. The phosphoric acid, thiocal, infiltrax, humic acid, penterra, as well as paper waste and gypsum were applied by hand sprayer to the soil surface and not incorporated. Wire mesh (6 mm opening size) was also used to reduce raindrop impact, where the wire mesh was laid and staked to the bed after tillage.

Table 4.1. Composition of the paper waste and gypsum used as amendment to improve soil aggregation.

Paper waste				Gypsum	
EC	0.28 ds/m	Total nitrogen	1.18 %	Calcium %	22
Chloride	81 ppm	Potassium	114 ppm	Magnesium %	0.01
Bulk Density	0.11g/cm^3	Sodium	357 ppm	Sodium %	0.10
pH (H_2O)	7.73	Moisture	75 % W/W	Potassium %	0.01
Magnesium	150 ppm	Organic carbon	50 %	Sulphur %	18
Ammonium	36 kg/ha	Calcium	3292 ppm	Moisture content %	4.10

4.2.2 Crust density and penetration resistance

The density of the surface crusts were measured by the water replacement procedure described by Cresswell and Hamilton (2002). Briefly, a thin plastic bag was placed within a 200 mm diameter ring. The bag was then filled with water to a known datum and removed to enable the soil crust to be removed by scraping and use of a portable vacuum. The water filled bag was replaced on the soil surface and the volume of excavated soil determined as the volume of water required to fill the bag back to the

original datum. Density was calculated by the oven dry mass of the extracted soil crust divided by the second volume of water to reach the datum. Penetration resistance of the soil crust was measured using a CL-700 pocket Penetrometer (kg/cm^2). Measurements were taken on day 8 and 42 for all treatments, and for the control on day 1.

4.2.3 Aggregate stability

As described in Chapter 2.2.3, soil aggregates were collected at 0 - 5 cm depth by small hand shovel then placed in large containers for transport to the laboratory. Aggregates were oven dried at 40^{o}C for 24 hours, then carefully hand sieved to retain the 2.00 – 4.75 mm size fraction for determining aggregate stability. Aggregate stability was determined by wet sieving, which was conducted using an Eijkelkamp wet sieving apparatus, in which four gram samples of the 2.00 – 4.75 mm aggregates were placed on a 250 μm sieve, which were then slowly immersed in distilled water and moved up down for three minutes (oscillation speed was 36 cycles per minute). Aggregate stability was determined as the proportion of aggregates retained on the 250 μm sieve after removing the remaining coarse fraction (> 250 μm) from the stable aggregates by ultrasonic dispersion and re-sieving.

4.2.4 Infiltration rate

Infiltration was measured using mini disk infiltrometer (Decagon devices) at -0.1 and -0.3 kPa suction, in which three replications were obtained per treatment. The infiltrometer was connected to the surface crust with a thin layer (1-2 mm) of < 250 μm sand. Infiltration measurements were conducted for 15 – 25 min duration per tension setting. Measurements were taken on day 8 and 42 for all treatments, and for the control on day 1, 8 and 42.

4.2.5 Selected soil chemical properties and statistical analysis

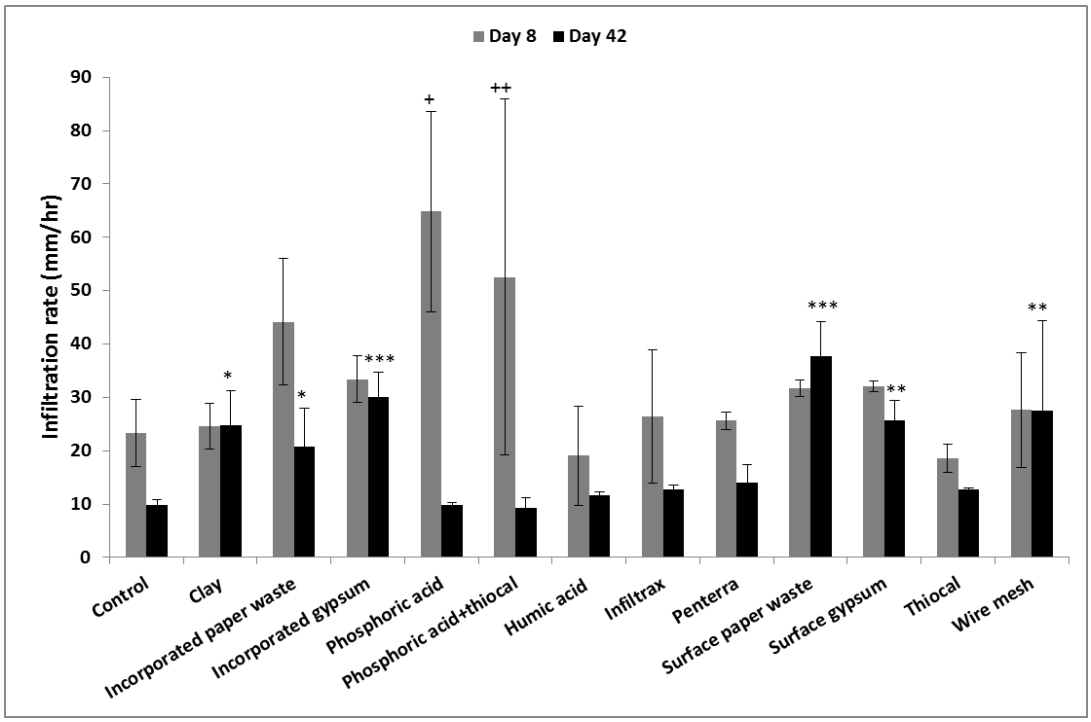
Soil chemical analyses were conducted by CSBP laboratories (Bibra Lake, Western Australia) on the 2.00 – 4.75 mm soil aggregates from bulked sample on day 8 and 42, and for the control on day 1. Analysis was conducted according to Rayment and Lyons (2011), including; soil pH in water and in $CaCl_2$, electrical conductivity (4A1, 4B3, 3A1), soluble and exchangeable cations were determined by using a soil solution ratio of 1:5 (5A4, 15E1). The exchangeable acidity Al^{+3} and H^{+} were measured by titration with NaOH and HPWl following extraction with 1m KCl in a 1:5 ratio for one hour (15 G1). Calcium carbonate percentage was determined by using dilute hydrochloric acid (19B2). Reactive Al^{3+} and Fe^{3+} were determined by Tamms reagent (oxalic acid/ammonium oxalate). Particle size of the whole soil (0 -5) was measured by mid infrared (MIR-6B4b) by CSBP (Rayment & Lyons 2011).

The influence of each treatment on bulk density, penetration resistance, hydraulic conductivity and aggregate stability relative to the control, were determined using One-Way Analysis of Variance (ANOVA) in SPSS (version 21).

4.3 Results

4.3.1 Effect of soil treatments on infiltration rate

At day 8, the phosphoric acid and phosphoric acid plus thiocal treatments had significantly higher infiltration than the control at $P < 0.05$ (Figure 4.1). At day 42, the incorporated and surface gypsum, incorporated and surface paper waste, wire mesh, and clay treatments had significantly greater infiltration rate compared with the control. Moreover, no significant differences existed between the control and humic acid, infiltrax, penterra and thiocal treatments at any of the sampling date.

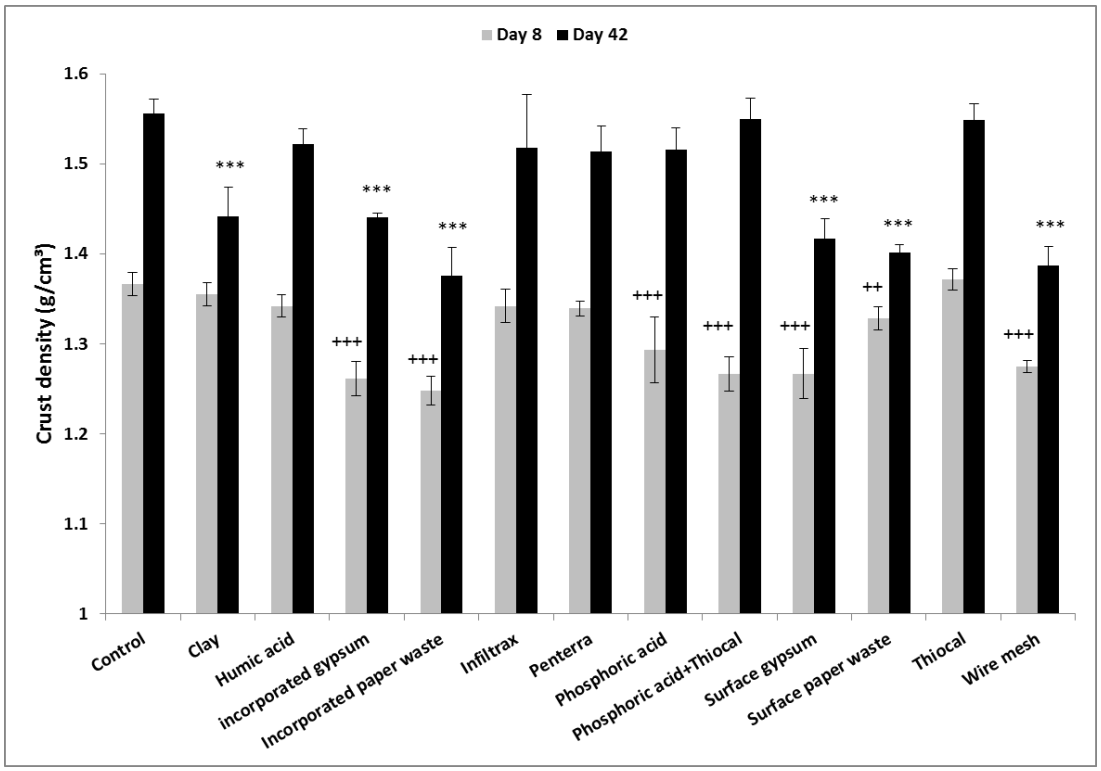


* or + =significant difference to the control at P<0.05, ** or ++ =significant difference to the control at P<0.01 and *** or +++ = significant difference to the control at P<0.001.

Figure 4.1. Effect of different treatments on infiltration rate at day 8 and day 42 after applied of products (infiltration rate measured at -1cm suction). Error bars indicate ±1 standard deviation.

4.3.2 Effect of soil treatments on crust density

In the control treatment, crust density increased from 1.12 g/cm^3 to 1.37 g/cm^3 between day 1 and day 8, to 1.54 g/cm^3 by day 42. Application of incorporated and surface paper waste, incorporated and surface gypsum, phosphoric acid, phosphoric acid & thiocal and wire mesh treatments reduced the crust density at day 8, relative to the control (Figure 4.2). Similarly, at day 42, application of clay, incorporated and surface paper waste, incorporated and surface gypsum and wire mesh treatments had significantly lower crust density than the control. The humic acid, infiltrax, penterra and thiocal treatments had no significant effect on crust density relative to the control at any of the sampling date.

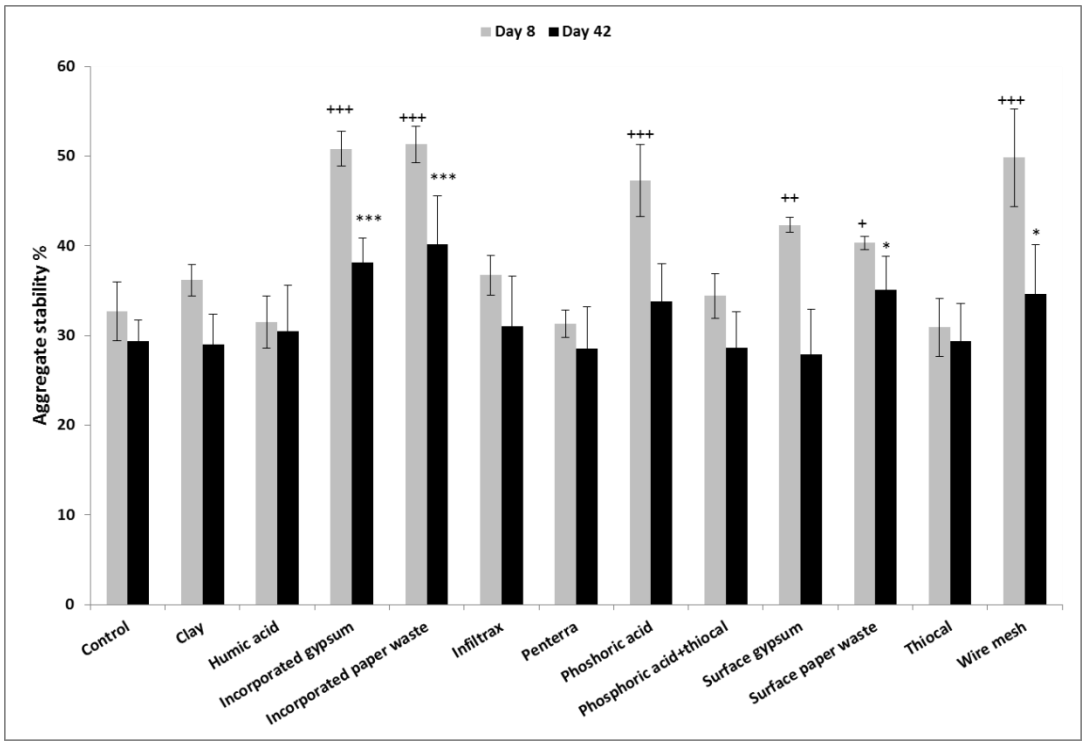


**or ++=significant difference to the control at P<0.01 and ***or +++ = significant difference to the control at P<0.001,

Figure 4.2. The effect of different treatments on the crust density at day 8 and day 42 of starting the trial. Error bars indicate ±1 standard deviation.

4.3.3 Effect of soil treatments on aggregate stability

In the control, aggregate stability significantly decreased from 59 % to 33 % between day 1 and day 8, and to 29 % by day 42. Aggregates were significantly more stable than the control in the incorporated paper waste, incorporated gypsum, phosphoric acid, wire mesh, surface paper waste and surface gypsum treatments at day 8 (Figure 4.3). At day 42, aggregate stability values of incorporated paper waste, incorporated gypsum, surface, surface paper waste and wire were significantly higher than the control. The clay, humic acid, infiltrax, penterra, phosphoric acid plus thiocal and thiocal treatments had no significant effect on aggregate stability at any of the sampling date.

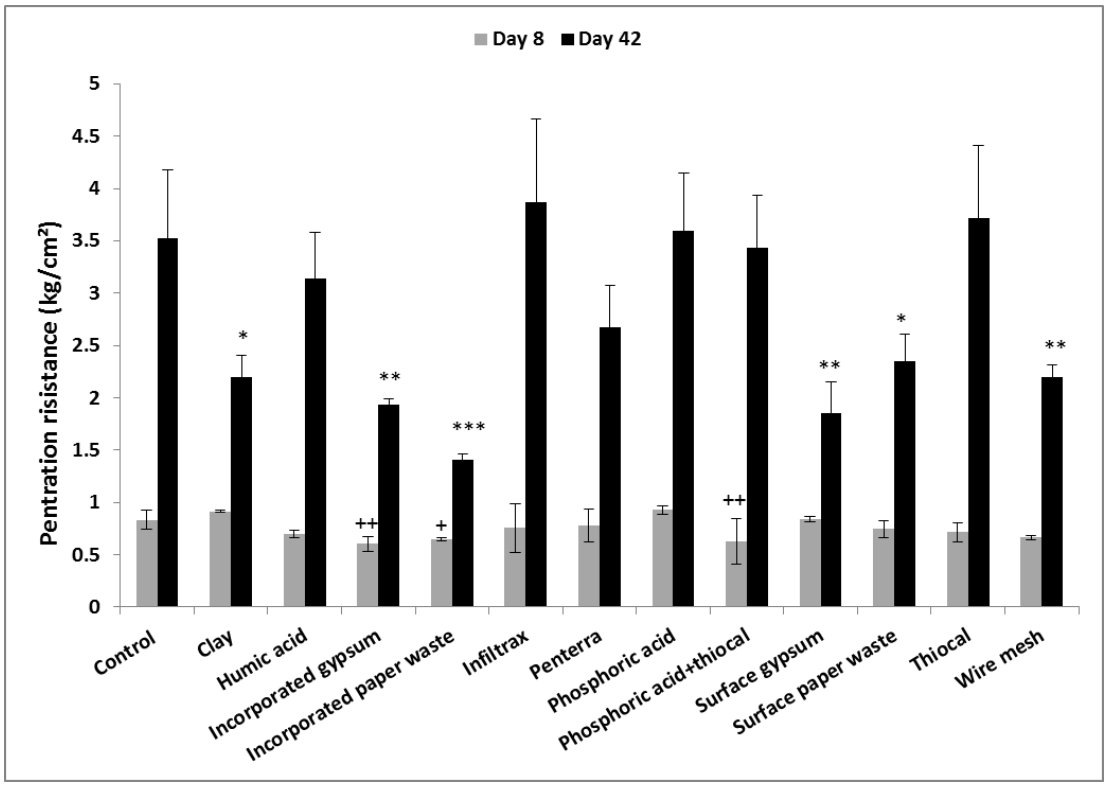


* or + =significant difference to the control at P<0.05, ** or ++ =significant difference to the control at P<0.01 and *** or +++ = significant difference to the control at P<0.001.

Figure 4.3. The effect of different treatments on aggregate stability at day 8 and day 42 of starting the trial. Error bars indicate ±1 standard deviation.

4.3.4 Effect of soil treatments on penetration resistance

Application of incorporated paper waste, incorporated gypsum and phosphoric acid & thiocal treatments resulted in significantly lower penetration resistance than the control at day 8 (Figure 4.4). The incorporated paper waste, incorporated gypsum, surface gypsum, clay, wire mesh and surface paper waste treatments reduced the penetration resistance at day 42. The humic acid, infiltrax, penterra, phosphoric acid and thiocal treatments had no significant effect on penetration resistance at any of the sampling dates.



* or + =significant difference to the control at P<0.05, ** or ++=significant difference to the control at P<0.01 and *** or +++ = significant difference to the control at P<0.001.

Figure 4.4. The effect of different treatments on the pentration resistance at day 8 and day 42 of starting the trial. Error bars indicate ±1 standard deviation.

4.3.5 Effect of soil amendments on chemical soil properties

By day 8, soil organic carbon increased from 1.63 % in the control to 1.95 % for the incorporated paper waste treatment, to 1.80 % for phosphoric acid treatment and to 189 % for the surface paper waste treatment as shown in the Table 4.2. Exchangeable Ca^{2+} increased in most treatments, from 6.93 meg/100g in the control to 10.25 meg/100g in the surface gypsum treatment, to 8.49 meg/100g in the surface paper waste treatment and to 7.59 meg/100g in the incorporated gypsum treatment. Conductivity increased from 0.074 ds/m in the control to 0.148 ds/m in the incorporated gypsum treatment, and to 181 ds/m in the surface gypsum treatment. Exchangeable Na^{+} decreased from 0.32 meg/100g in the control, to 0.16 meg/100g in the surface gypsum treatment. Calcium carbonates increased from 0.27 % in the control to 0.53 %, 0.74 %, 0.79 % and to 0.97 %

in the incorporated gypsum, incorporated paper waste, penterra and surface gypsum treatments respectively. Soluble Ca^{2+} increased from 0.38 meq/L in the control to 2.50 meq/L in the surface gypsum treatment.

At day 42, soil organic carbon increased from 1.56 % in the control to 2.27 % in the incorporated paper waste treatment, and to 1.98 % in the surface paper waste treatment (Table 4.3). Conductivity increased from 0.258 ds/m in the control to 0.386 ds/m in the incorporated gypsum treatment, and to 0.503 ds/m in surface gypsum treatment. Exchangeable Ca^{2+} increased from 6.86 meq/100g in the control to 8.14 meq/100g in the incorporated gypsum treatment, 9.16 meq/100g in the incorporated paper waste treatment, 9.24 meq/100g in the surface paper waste treatment, and to 9.41 meq/100g in the surface gypsum treatment. Calcium carbonate increased from 0.40 % in the control to 0.75 % in the surface paper waste treatment. Soluble calcium increased from 0.56 meq/L in the control to 1.82 meq/L in the incorporated gypsum, and to 2.50 meq/L in the surface gypsum treatment, while soluble Na^{+} decreased from 0.31meq/L in the control to 0.22 meq/L in the incorporated paper waste treatment, and to 0.19 meq/L in the surface gypsum treatment.

Table 4.2. Characteristics of the soil sampled in the experiment (depth: 0-5) at day 8 of application of treatments.

Treatments	OC %	EC (ds/m)	pH	Exc. Al^{+3} (meq/100g)	Exc. Ca^{+2} (meq/100g)	Exc. Mg^{+2} (meq/100g)	Exc. K^{+} (meq/100g)	Exc. Na^{+} (meq/100g)	Reactive Iron (mg/Kg)	CaCO3 %	Soluble Ca^{+2} (meq/L)	Soluble Mg^{+2} (meq/L)	Soluble K^{+} (meq/L)	Soluble Na^{+} (meq/L)	Reactive Al^{+3} (mg/Kg)
Control	1.63	0.074	6.3	0.104	6.93	2.04	0.58	0.32	2517.8	0.27	0.38	0.26	0.23	0.25	1959
Clay	1.71	0.100	6.3	0.104	7.36	2.42	0.68	0.35	2426.2	0.74	0.35	0.24	0.20	0.26	1979
Incorporated paper waste	1.95	0.089	6.5	0.112	7.40	2.17	0.65	0.28	2394.8	0.32	0.38	0.25	0.21	0.24	1895
Incorporated gypsum	1.69	0.148	6.1	0.097	7.59	1.83	0.65	0.23	2461.1	0.53	0.81	0.37	0.24	0.22	1954
Humic acid	1.71	0.070	6.4	0.096	7.31	1.93	0.85	0.26	2494.3	0.36	0.43	0.26	0.27	0.20	2244
Infiltrax	1.75	0.072	6.3	0.151	7.00	1.86	0.93	0.41	2611.0	0.36	0.54	0.31	0.34	0.26	2299
Penterra	1.43	0.081	6.3	0.126	7.19	1.98	0.82	0.25	2652.6	0.79	0.45	0.27	0.27	0.21	2365
Phosphoric acid & thiocal	1.72	0.060	6.0	0.192	7.47	2.18	0.79	0.26	2694.4	0.34	0.35	0.26	0.24	0.18	2431
Phosphoric acid	1.80	0.096	6.0	0.141	7.15	2.04	0.89	0.25	2607.8	0.48	0.44	0.26	0.27	0.19	2488
Surface paper waste	1.89	0.118	7.0	0.093	8.49	1.92	0.80	0.26	2354.2	0.46	0.45	0.25	0.25	0.21	1925
Surface gypsum	1.72	0.181	6.3	0.082	10.25	1.97	0.71	0.16	2621.2	0.97	2.50	1.25	0.28	0.16	2323
Thiocal	1.77	0.057	6.3	0.111	7.26	2.11	0.87	0.27	2677.0	0.44	0.46	0.31	0.30	0.22	2385

Table 4.3. Characteristics of the soil sampled in the experiment (depth: 0-5) at day 42 of application of treatments.

Treatments	OC %	EC (ds/m)	pH	Exc. Al^{+3} (meq/100g)	Exc. Ca^{+2} (meq/100g)	Exc. Mg^{+2} (meq/100g)	Exc. K^{+} (meq/100g)	Exc. Na^{+} (meq/100g)	Reactive Iron (mg/Kg)	CaCO3 %	Soluble Ca^{+2} (meq/L)	Soluble Mg^{+2} (meq/L)	Soluble K^{+} (meq/L)	Soluble Na^{+} (meq/L)	Reactive Al^{+3} (mg/Kg)
Control	1.56	0.258	6.1	0.119	6.86	1.93	0.70	0.34	2389.9	0.40	0.56	0.33	0.30	0.31	1736
Clay	1.61	0.200	6.1	0.104	7.31	2.44	0.77	0.41	2417.1	0.35	0.57	0.37	0.27	0.36	1875
Incorporated paper waste	2.27	0.156	7.1	0.103	9.16	2.10	0.80	0.28	2305.9	0.41	0.45	0.23	0.22	0.22	1782
Incorporated gypsum	1.71	0.386	6.3	0.074	8.14	1.93	0.79	0.29	2353.8	0.39	1.82	0.34	0.33	0.28	1770
Humic Acid	1.68	0.240	6.3	0.093	7.87	1.92	0.77	0.36	2513.8	0.42	0.60	0.35	0.32	0.33	1890
Infiltrax	1.65	0.278	6.2	0.106	7.11	1.93	0.87	0.39	2594.1	0.39	0.61	0.37	0.37	0.36	1854
Penterra	1.60	0.279	6.2	0.109	7.11	2.06	0.76	0.35	2418.4	0.42	0.60	0.35	0.34	0.31	1833
Phosphoric acid + thiocal	1.75	0.197	6.2	0.124	7.22	2.09	0.77	0.31	2557.5	0.36	0.53	0.33	0.31	0.28	2217
Phosphoric Acid	1.76	0.191	6.1	0.091	7.23	1.97	0.76	0.31	2524.3	0.41	0.54	0.31	0.29	0.28	2108
Surface Paper waste	1.98	0.170	6.9	0.073	9.26	2.00	0.84	0.25	2332.7	0.75	0.59	0.29	0.28	0.22	1781
Surface Gypsum	1.68	0.503	6.3	0.074	9.41	1.74	0.80	0.20	2544.5	0.47	2.50	0.30	0.31	0.19	2016
Thiocal	1.73	0.236	6.1	0.126	7.72	2.06	0.93	0.41	2488.4	0.45	0.78	0.41	0.35	0.37	2041

4.4 Discussion

The effect of the different soil amendments on infiltration rate, aggregate stability, penetration resistance and crust density are summarised in Table 4.4. The incorporated gypsum and incorporated paper waste treatments were the most effective products for reducing the severity of soil crusting at both sampling dates (days 8 and 42). The surface paper waste, wire mesh and surface gypsum treatments improved all measures of soil crusting on at least one sampling date. The phosphoric acid, phosphoric acid & thiocal and clay treatments significantly improved three of the four measures of soil crusting, mostly at one sampling date. The phosphoric acid and phosphoric acid & thiocal treatments were only effective at day 8.

Table 4.4. Summary of the significant effects (yes) of the different treatments on infiltration rate, crust density, aggregate stability and penetration resistance at day 8 and day 42. Total refers to the number of significant improvements.

Treatments	Infiltration rate		Crust density		Aggregate stability		Penetration resistance		Total
	Day 8	Day 42	Day 8	Day 42	Day 8	Day 42	Day 8	Day 42	
Incorporated paper waste	x	yes	yes	yes	yes	yes	yes	yes	7
Incorporated gypsum	x	yes	yes	yes	yes	yes	yes	yes	7
Surface paper waste	x	yes	yes	yes	yes	yes	x	yes	6
Surface gypsum	x	yes	yes	yes	yes	x	x	yes	5
Phosphoric acid	yes	x	yes	x	yes	x	x		3
Phosphoric acid+thiocal	yes	x	yes	x	x	x	yes		3
Clay	x	yes	x	yes	x	x	x	yes	3
Wire mesh	x	yes	yes	yes	yes	yes	x	yes	6
Humic acid	x	x	x	x	x	x	x		0
infiltrax	x	x	x	x	x	x	x		0
Penttera	x	x	x	x	x	x	x		0

X = no significant effect

In this study, the application of incorporated and surface paper waste treatments increased infiltration rate and aggregate stability, and decreased crust density and penetration resistance relative to the control. As seen in the Table 4.1 and Table 4.2, the paper waste resulted in a notable increase in SOC. Paper waste was likely to have reduced crusting and increased infiltration via a range of processes: (1) increased organic carbon, (2) increased Ca^{+2}, (3) working as a aggregating agent (Kemper & Koch 1966), (4) reduced the wetting rate of soil aggregates, and (5) reduced bulk density. These decreased the susceptibility of the soil aggregates to break down and formation of soil crusting (Kemper & Koch 1966, Kemper & Rosenau 1986, Sullivan 1990, Leelamanie et al. 2013). Application of paper waste prior to bed formation and sowing appears to be valuable means of reducing soil crusting in low carbon soil, packet salad systems.

The incorporated gypsum and surface gypsum treatments significantly improved all measures of crusting. Chemical analysis showed that exchangeable and soluble Ca^{2+} increased while exchangeable and soluble Na^{+} decreased. Gypsum is known to act as a connective agent to bind soil particles together, leading to improve aggregate stability (Agassi et al. 1982), improved flocculation and reduced dispersion, resulting in increased water movement (Rengasamy et al. 1984, Miller & Scifres 1998, Qadir & Oster 2004).

The application of phosphoric acid and phosphoric acid & thiocal treatments increased infiltration rate and reduced crust density at day 8, but not day 42. Moreover, the phosphoric acid treatment increased aggregate stability while phosphoric acid & thiocal treatment reduced penetration resistance at day 8. The phosphoric acid & thiocal treatment increased exchangeable Ca^{+2} and deceased exchangeable Na^{+}, leading to

promoted aggregation, resulting in increased porosity, which reflected positively on infiltration rate and crust density at day 8. As these amendments were effective at day 8, they may prove effective of reducing crusting during seedlings emerge.

The wire mesh was observed to have improved all measures of crusting on at least one sampling date. Reduced crusting was attributed to the wire mesh reduced the impact of raindrop during rainfall or irrigation event, such that the kinetic energy applied to these treatments was lower than that of the control (Rienzi et al. 2013).

The application of the clay treatment significantly increased infiltration rate and reduced crust density and penetration resistance at day 42. It is likely that clay particles coated the sand grains, thus strengthening the bridges between soil particles (Singer et al. 1992). The ability of clay amendments to act as a connection agent among soil particles has been recognised (Levy & Mamedov 2002, Wagner et al. 2007). Furthermore, adding clay to soils may increase the polyvalent cations that have an ability to strengthen the bond between clay coated sands and SOC, resulting in more stable aggregates (Edwards & Bremner 1967).

4.5 Conclusion

No single treatment was able to prevent soil crusting, however some amendments significantly reduced soil crusting relative to the control. At both sampling dates, incorporated paper waste and gypsum reduced crust density and penetration resistance, and increased aggregate stability. Phosphoric acid treatment increased infiltration rate and aggregate stability, and reduced crust density only at day 8, whist wire mesh was only effective at day 42. In summary, results indicated that soil amendments such as gypsum, paper waste, phosphoric acid and wire mesh had the greatest ability to reduce

soil crusting. Therefore, these products were investigated in a replicated experiment including rate and treatment combinations in Chapter 5.

Chapter 5: Can soil crusting be reduced through application of gypsum, organic waste and phosphoric acid?

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Abstract

Soil crusting is a form of land degradation in which the breakdown of aggregates results in the formation of a thin impermeable layer on the soil surface. A preliminary experiment described in Chapter 4 indicated that application of paper waste, gypsum, phosphoric acid and covering the soil surface with wire mesh showed potential for reducing soil crusting. This study evaluated the use of products for reducing the severity of soil crusting, whilst also testing different approaches for measuring the severity and likelihood of soil crust formation. Gypsum was applied at 0.25 and 0.50 kg/m^2, paper waste was applied at 1.0, 2.5 and 7.5 kg/m^2, and phosphoric acid was applied at 80 and 160 ml/m^2. Combinations of these products included: (i) wire mesh & 0.50 kg/m^2 gypsum (WM+HG), (ii) 0.50 kg/m^2 gypsum & 80 ml/m^2 phosphoric acid (HG+LP), (iii) 2.5 kg/m^2 paper waste & 0.50 kg/m^2 gypsum & 80 mls/m^2 phosphoric acid (MPW+HG+LP) and (iv) 7.5 kg/m^2 paper waste & 160 ml/m^2 phosphoric acid (HPW+HP). The likelihood of crust formation was inferred from aggregate stability determined by rainfall simulation and wet sieving, whilst the severity of soil crusting

was inferred from crust density, hydraulic conductivity and penetration resistance. The four measures of crust severity/likelihood were highly correlated with each other (R^2 = 0.57 to 0.80). The HPW+HP, MPW+HG+LP and MPW treatments increased hydraulic conductivity by 72 %, 66 % and 45 % respectively, and aggregate stability determined by rainfall simulation by 28 %, 37 % and 39 % respectively. These treatments reduced surface soil density by 10 %, 7 % and 6 % respectively, and penetration resistance by 33 %, 37 % and 34 % as average at all five sampling dates (days 8, 14, 28, 71 and 197). Moreover, the high rate of gypsum significantly reduced bulk density by 7 % and penetration resistance by 26 %, yet had no effect on any other measure of crusting. Phosphoric acid (HP) significantly increased aggregate stability determined by rainfall simulation by 29 % (days 8, 14, 28 and 71), reduced bulk density by 6 % (days 8 and 14) and increased hydraulic conductivity at day 8 by 110 %. Reduced the severity and or likelihood of crust formation following application of gypsum and paper waste were attributed to the increased in Ca^{+2} and soil organic carbon. The paper waste and gypsum were the most effective amendments over the duration of the trial while phosphoric acid reduced the severity of crust formation in the 14 days after application. Recommendations are provided on the efficiency of different approaches for measuring soil crusting, in which penetration resistance is preferable because of its high correlation with other measurements and being the least time consuming.

5.1 Introduction

Houston's Farm is one of the most successful farming enterprises in Tasmania, Australia, and supplies packet salad to more than 1200 major supermarkets across Australia. Frequent cultivation and low residue input have resulted in rapid loss of soil carbon, reduction in aggregate stability and formation of surface soil crusting. These

crusts have resulted in ponding on beds, increased runoff and erosion, poor irrigation efficiency and decreased seedling emergence (Hardie et al. 2013). Splashing of loose soil onto the leafy crop also reduces crop quality and renders it susceptible to increased fungal disease.

Soil crusting is a form of land degradation in which the breakdown of aggregates results in the formation of a thin impermeable layer on the soil surface (Sumner & Miller 1992, Fan et al. 2008). Soil crusts are formed by one or a multiple of processes including raindrop impact, slaking, dispersion and settlement of detached particles (Le Bissonnais 1996). According to Bresson and Cadot (1992), soil crusts are classed as structural or depositional. Structural crusts result from break down of surface macro-aggregates into smaller fragments, which then form an impermeable, thin layer on the soil surface. Whereas, depositional crusts result from the transport and deposition of fine soil particles away from their point of the origin (Boiffin 1986).

Determining the effectiveness of soil amendments on soil crusting is problematic due to the difficulty associated with measuring soil crusting over time. The risk or likelihood that a soil will form a surface crust may be inferred by measuring aggregate stability, whereas the severity of crust formation can be inferred from measures of infiltration, runoff, penetration resistance and surface soil density (Le Bissonnais 1996, Cresswell & Hamilton 2002, Materechera 2009, Souza et al. 2014, Nciizah & Wakindiki 2016). A number of studies have estimated the severity of soil crusting from penetration resistance (Drahorad & Felix-Henningsen 2013, Pulido et al. 2014). Penetration resistance is a simple, inexpensive means to estimate crust severity that is also related to the physical effort required for seedlings to emerge through the soil surface (Clark & David 2008). However, penetration resistance is also closely related to soil moisture

content (Tarkiewicz & Nosalewicz 2005, Pham et al. 2012), such that results are difficult to compare over time or between sites at different moisture contents.

Cresswell and Hamilton (2002) developed a water replacement procedure to measure the density of surface crusts, in which the volume of the excavated crust is determined by the volume of water required to return to a pre-excavation datum. However, review of the literature indicates the procedure has not been widely adopted by subsequent researchers. The severity of soil crusting can also be estimated from the effect of crusting on infiltration and runoff (Agassi et al. 1985, Sumner & Miller 1992). For example, McIntyre (1958) reported that 0.1 mm thick crusts reduced infiltration rate 10 times compared with non-crusted soil. Moreover, Stern et al. (1991) reported that crust formation reduced steady state infiltration from 8.0 mm/h to 4.5 mm/h.

Despite the wide spread occurrence of soil crusting (Sumner & Miller 1992), and the impact of soil crusts on crop production, few studies have evaluated the use of different products on reducing soil crusting. There is a considerable body of research that demonstrates that application of carbon to soils in the form of crop residuals, organic waste and compost improves soil aggregation and aggregate stability (Tisdall & Oades 1982, Fierro et al. 1999, Aggelides & Londra 2000, Rasse et al. 2000, Tejada & Gonzalez 2003, Tejada et al. 2009, D'Hose et al. 2014). However, few studies have sought to determine if the improved aggregation following carbon addition reduces the formation or severity of soil crusts.

In sodic soils (ESP > 5) and some non-sodic soils, addition of gypsum and other electrolytes have been shown to improve aggregation and reduce soil crusting (McKenzie & So 1989, Wallace 1994, Ellington et al. 1997, Hanay et al. 2004, Amezketa et al. 2005, Dang et al. 2010). In sodic soils, application of gypsum acts by

replacing exchangeable Na^+ with Ca^{2+}, and by increasing electrolyte concentration in the soil water (Quirk & Schofield 1955, Awadhwal & Thierstein 1985, Valzano et al. 2001). This acts to prevent clay swelling and/or dispersion, leading to reduced crust formation (Verba & Devyatykh 1992, Qadir et al. 1996, Chorom & Rengasamy 1997, Ellington et al. 1997, Ilyas et al. 1997). In non-sodic soils, Chan (1995) also demonstrated that addition of gypsum in combination with straw to a sandy soil reduced raindrop impact and slaking by swelling, which they attributed to the increased electrolyte concentration of the water in soil pores and reduced wetting rate. Amezketa et al. (2005) also reported that two of three different forms of gypsum reduced soil crusting in a sodic soil, whilst curiously all three forms of gypsums reduced crusting in a non-sodic soil.

A small number of studies also indicate that application of phosphoric acid may reduce soil crusting. For example, Robbins et al. (1972) reported that the reduction in soil crusting resulted from increased aggregate stability by dissolving most of the carbonates in the surface layer and formation of soluble Ca and Mg phosphates that act as aggregating agents among soil aggregation. Thein (1976), and Ortas and Lal (2012) demonstrated that aggregate stability and total porosity were positively influenced by application of phosphoric fertilizers. They attributed this to the positive effect of phosphoric fertilizers on soil organic carbon, labile carbon and the ratio of soil carbon to nitrogen (Ghani et al. 2003, Moore et al. 2011, Ortas & Lal 2012).

In this Chapter, we evaluate (i) methods for measuring the severity and likelihood of crust formation over time and (ii) the effectiveness of a range of soil amendments on soil crusting, seedling emergence and crop yield in an intensively cultivated, low carbon, sandy clay loam soil used for packet salad production.

5.2 Material and methods

5.2.1 Site description and treatment application

As described in Chapter 4, the experiment was conducted on a commercial packet salad farm in the Coal River Valley in southern Tasmania (42.72532^{o} South, 147.43182^{o} East). The climate is defined as cool temperate with 500 mm of annual rainfall, yearly mean maximum temperature range of 12 – 22 ^{o}C and mean minimum temperature range of 4 – 12 ^{o}C (Bureau of Meteorology 2015). The soil is derived from Tertiary – Quaternary sediments capped by a thin layer of Aeolian fine sands and silts. Soil at the site was classified as a Brown Chromosol, however only the topsoil (0-5 cm depth) is considered in this study. The top soil contained 55.9 % sand, 10.8 % silt, and 33.3 % clay; and had a pH(water) of 6.0, electrical conductivity ($EC_{1:5}$) of 0.42 dS/m, organic carbon of 2.3 %, cation exchange capacity (ECEC) of 13.9 meq/100g soil, and exchangeable sodium percentage (ESP) of 3.96 %.

Prior to the experiment reported in this paper, a preliminary experiment was conducted at the site using single rates of variety of treatments from 18 of Dec 2014 to 27 of Jan 2015. Treatments included phosphoric acid (75 ml/m^2), infiltrax (20 ml/$m^{2)}$, thiocal (1 ml/m^2), humic acid (2.9 ml/m^2), penterra (0.47 ml/m^2), phosphoric acid & thiocal, subsoil clay (13 kg/m^2), incorporated gypsum (0.5 kg/m^2), surface gypsum (0.5 kg/m^2), incorporated paper waste (8 kg/m^2), surface paper waste (3 kg/m^2) and wire mesh. Results of preliminary experiment reported in Chapter 4 indicated that paper waste, gypsum and phosphoric acid showed potential to be considered for further evaluation.

This experiment was conducted during the period between 25 of Feb and 4 of Sep 2015. The experiment was a randomised complete block design (RCBD) with 11 treatments and a control, with three replicates per treatment. The experiment contained 12 beds, in

which every second bed was sown, whilst alternative beds were left fallow (non-cropped) to facilitate measurements of soil crusting. Beds were 1.2 m wide, 51 m long and 0.4 m high. Beds contained 6 plots, each 3.0 m long, with a 6.0 m buffer between plots. In total, there were 12 control plots, and 60 treatment plots, in which 36 beds were cropped and 36 beds left fallow.

Based on results from preliminary experiment, treatments included paper waste, gypsum, phosphoric acid and covering the soil surface with wire mesh. Gypsum was applied at two rates 0.25 kg/m^2 (LG) and 0.50 kg/m^2 (HG). The composition of the gypsum is presented in Table 5.1. Due to strict food safety protocols, manure based composts are prohibited in packet salad production, as such a newsprint waste was sourced from Norske Skog paper mill as an organic amendment. The paper waste consisted of partly decomposed wood/paper fibre, which was high in organic carbon (50 %) and Ca^{2+} (3292 ppm) (Table 5.1). The paper waste was applied within 24 hours of being obtained from the paper mill factory at three rates 1.0 kg/m^2 (LPW), 2.5 kg/m^2 (MPW) and 7.5 kg/m^2 (HPW). Phosphoric acid was applied at 22% concentration at two rates 80 mls/m^2 (LP) and 160 mls/m^2 (HP). Stainless steel wire mesh with an opening size of 6 mm and 1 mm diameter wire was laid on the soil surface in combination with 0.50 kg/m^2 gypsum (WM+HG), in which the wire mesh was intended to reduce rain drop impact while allowing crops to emerge through the wire. Other combinations of products included: (i) 0.50 kg/m^2 of gypsum + 80 mls/m^2 of H_3PO_4 (HG+LP), (ii) 2.5 kg/m^2 of paper waste + 0.50 kg/m^2 of gypsum + 80 mls/m^2 of H_3PO_4 (MPW+HG+LP) and (iii) 7.5 kg/m^2 of paper waste + 160 mls/m^2 of H_3PO_4 (HPW+HP).

Paper waste and gypsum were spread on the soil surface by hand directly after tillage and bed formation, then incorporated to a depth of 5 – 7 cm using a rotary hoe. The

other treatments were established one week later without further cultivation prior to sowing. The phosphoric acid was applied by hand sprayer to the soil surface and not incorporated. Wire mesh was laid on the soil surface and staked to the bed after sowing. The cropped beds were managed as per normal practice, the alternate beds were sown with spinach (*Spinacia, olerace*) transplants on the same day as the treatments were applied (day 1) and harvested on day 30. The beds were then left fallow for 105 days before being re-tilled and sown with mizuna (*Brassica rapa* var. *nipposinic)* transplants on day 135, and harvested on day 197. Long fallows between crops are normal practice for pest and disease control. Emergence of the spinach seedlings was assessed in each plot using a 120 x 15 cm quadrat. Crop yield (spinach and mizuna) were harvested in each plot from a 123 x 48 cm quadrat, and reported as fresh green weight.

Table 5.1. Composition of the paper waste and gypsum used as amendments to potentially improve soil aggregation.

Paper waste				Gypsum	
EC	0.28 ds/m	Total nitrogen	1.18 %	Calcium %	22
Chloride	81 ppm	Potassium	114 ppm	Magnesium %	0.01
Bulk Density	0.11g/cm^3	Sodium	357 ppm	Sodium %	0.10
pH (H_2O)	7.73	Moisture	75 % W/W	Potassium %	0.01
Magnesium	150 ppm	Organic carbon	50 %	Sulphur %	18
Ammonium	36 kg/ha	Calcium	3292 ppm	Moisture content %	4.10

In the preliminary experiment (Chapter 4), difficulty was encountered measuring crust density and infiltration once the crop had emerged as it was not possible to remove the crop without disturbing the surface crusts. Consequently, all soil physical measurements were conducted on the uncropped fallow beds to which treatments were also applied. It is accepted that crop development may have reduced raindrop impact, and thus lessened the severity of crusting on the cropped beds compared with the uncropped beds. However, visual inspection and data presented in this study demonstrate the crusts formed rapidly following sowing, such that the crusts existed prior to crop emergence or

canopy closure. Consequently, the severity of crusting reported in this study may be overstated for cropped soils due to the absence of crops from the measured beds, values of crust severity are believed to be typically of the prolonged fallow periods, and that comparison of results between treatments are valid. Aggregate stability, infiltration rate, crust density and penetration resistance were measured on the adjacent fallow beds on day 1 (sowing) for the control plots, and day 8, 14, 28, 71 and 197 for all treatments including the control.

5.2.2 Crust density

As described in Chapter 4.2.2, the density of the surface crusts were measured by the water replacement procedure described by Cresswell and Hamilton (2002). A thin plastic bag was placed within a 200 mm diameter ring. The bag was then filled with water to a known datum and removed to enable the soil crust to be removed by scraping and portable vacuum. The water filled bag was replaced on the soil surface and the volume of excavated soil determined as the volume of water required to fill the bag back to the original datum. Density was calculated by the oven dry mass of the extracted soil crust divided by volume of water to reach the datum. Crust density was measured in triplicate from all treatments on day 8, 14, 28, 71 and 197, and for the control on day 1.

5.2.3 Infiltration rate and hydraulic conductivity

As described in Chapter 4.2.3, infiltration was measured using mini disk infiltrometer (Decagon devices) at -0.1 and -0.3 kPa suction for three replicates per treatment. The infiltrometer was connected to the surface crust with a thin layer (1-2 mm) of < 250 μm sand. Infiltration measurements were conducted for 15 – 25 min duration per tension setting. To overcome the effect of moisture content on infiltration, results were

presented as hydraulic conductivity, which was calculated according to Ankeny et al. (1991).

5.2.4 Aggregate stability and penetration resistance

As described in Chapter 2.2.3 and 4.2.2, soil aggregates were collected at 0 - 5 cm depth by small hand shovel then placed in large containers for transport to the laboratory. Aggregates were oven dried at 40^{o}C for 24 hours, then carefully hand sieved to retain the 2.00 – 4.75 mm size fraction for determining aggregate stability.

Aggregate stability was determined by wet sieving and rainfall simulation. Wet sieving (WS) was conducted using an Eijkelkamp wet sieving apparatus, in which 4 gram samples of the 2.00 – 4.75 mm aggregates were placed on a 250 μm sieve, and then slowly immersed in distilled water and moved up down for three minutes (oscillation speed was 36 cycles per minute). Aggregate stability was determined as the proportion of aggregates retained on the 250 μm sieve after removing the remaining coarse fraction (> 250 μm) from the stable aggregates by ultrasonic dispersion and re-sieving.

Aggregate stability was also determined by rainfall simulation by mounting a Cornell sprinkle infiltrometer in a wooden frame 1.84 m above 30 g of the soil aggregates. The Cornell infiltrometer applied tap water (EC = 70 μs/cm) from 130 needles over a 314 cm^2 area at a constant rate of 36 cm/hr for four minutes. The mean weight diameter (MWD) of the droplets was determined by the flour pellet method (Laws & Parsons 1943) to be 3.09 ± 0.14 mm. The 2.00 – 4.75 mm sieved soil aggregates were placed on a 250 μm sieve mounted above filter paper in a large funnel to capture the disaggregated particles. Aggregate stability was calculated as the mass of aggregates remaining on the 250 μm sieve, after accounting for coarse fraction by ultrasonic disruption and re-sieving.

Penetration resistance of the soil crust was measured using a CL-700 Pocket Penetrometer (kg/cm^2), in which 10 replicates were taken in each plot on day 8, 14, 28, 71 and 197, and for the control on day 1.

5.2.5 Selected soil chemical properties

Soil chemical analyses were conducted by CSBP Laboratories (Bibra Lake, Western Australia) on the 2.00 – 4.75 mm soil aggregates from a bulked sample of the three replicate plots for each treatment on day 8, 14, 28, 71 and 197, and for the control only on day 1. Analysis conducted according to Rayment and Lyons (2011), included soil pH in water and in $CaCl_2$, electrical conductivity (4A1, 4B3, 3A1), soluble and exchangeable cations were determined by using a soil solution ratio of 1:5 (5A4, 15E1). The exchangeable acidity Al^{+3} and H^+ were measured by titration with NaOH and HPWl following extraction with 1M KCl in a 1:5 ratio for one hour (15 G1). Calcium carbonate percentage was determined by using dilute hydrochloric acid (19B2). Reactive Al^{3+} and Fe^{3+} were determined by Tamms reagent (oxalic acid/ammonium oxalate). ECEC was calculated as the sum of cations (Ca^{2+}, Mg^{2+}, Na^+, K^+ and Al^{3+}). Soil organic carbon was determined by wet oxidation, 6A1 (Walkley & Black 1934). Sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP) were calculated according to Rengasamy and Marchuk (2011). Particle size of the whole soil (0 -5 cm) was measured by mid infrared (MIR-6B4b) by CSBP (Rayment & Lyons 2011).

5.2.6 Statistical analysis

The different approaches for measuring crust severity and/or likelihood of crust formation were evaluated by calculation of the within treatment coefficient of variation (COV), and between treatments COV. A small within treatment COV indicates analytical precision, while a large between treatments COV favours the ability to

discriminate between treatments. Degree of association between different measures of crust severity and likelihood of crust formation was explored by Spearman correlation in SPSS (version 21). The influence of each treatment on bulk density, penetration resistance, hydraulic conductivity and aggregate stability relative to the control was explored using One-Way Analysis of Variance (ANOVA) in SPSS (version 21). The effect of treatments on soil chemical attributes was explored using One-Way ANOVA in SPSS (version 21) for the average of five sampling dates (treated versus control plots).

5.3 Results

5.3.1 Evaluation of soil parameters

The most precise measure of crust severity/likelihood (lowest within treatment COV) was crust density while the least precise method was hydraulic conductivity (Table 5.2). However, hydraulic conductivity had the greatest ability to discriminate between treatments (high between site COV) followed by the penetration resistance procedure. Aggregate stability determined by rainfall simulation was better of discerning differences between treatments (high between treatments COV) than wet sieving procedure.

Table 5.2. Time per replicate and coefficient of variation (COV) between and within treatments, as estimates of crust severity and or likelihood of crust formation.

Parameters	Equipment	Time per replicate	COV between treatments %	COV within treatment %
Penetration resistance	Packet penetration	10 sec	13.02	17.64
Hydraulic conductivity	Mini disk	40 min	21.95	35.35
Wet sieving	Eijkelkamp apparatus	5 min	6.71	7.53
Rainfall simulation	Cornell infiltrometer	15 min	11.88	11.29
Bulk density	Water replacement	20 min	5.07	2.37

5.3.2 Correlation between soil physical properties

The four measures of crust severity/likelihood of crust formation were highly correlated with each other (Table 5.3). The highest correlation was found between penetration resistance and crust density ($R^2 = 0.80$). Penetration resistance was highly correlated with the other three measures, in which R^2 values ranged from 0.74 to 0.80. In contrast, hydraulic conductivity was poorly correlated with the other measures of crust severity/likelihood in which values ranged from R^2 0.57 to 0.74.

Table 5.3. Correlations between measured soil physical properties including aggregate stability (rainfall simulation and wet sieving procedures), crust density, hydraulic conductivity and penetration resistance.

	Rainfall simulation	Wet sieving	Bulk density	Hydraulic conductivity
Wet sieving	0.74^{**}			
Crust density	-0.72^{**}	-0.70^{**}		
Hydraulic conductivity	0.65^{**}	0.57^{**}	-0.65^{**}	
Penetration resistance	-0.74^{**}	-0.77^{**}	0.80^{**}	-0.74^{**}

**=significant at $P<0.001$, n = 72

5.3.3 Soil properties post tillage

Soil physical properties immediately after sowing and prior to irrigation/rainfall for the three control plots are presented in Table 5.4. Bulk density, penetration resistance and hydraulic conductivity were 1.08 g/cm^3, 0.41 kg/cm^3 and 114 mm/hr respectively.

Aggregate stability determined by rainfall simulation was 49 %, while aggregate stability determined by wet sieving was 75 %. The soil exchange complex was dominated by exchangeable Ca^{2+} (66 %) followed by exchangeable Mg^{2+} (20 %) while the amount of exchangeable Na^{+} was only 3.96 % of the ECEC and thus the top soil is not considered to be sodic. The amount of soil organic carbon was 2.29 %, which is considered high for intensively cropped sandy clay loam soils in the region.

Table 5.4. Summary of the soil physical and chemical properties at sowing, prior to irrigation or rainfall.

Soil property	Value	Soil property	Value	Soil property	Value
Aggregate stability (RS) %	49	Exch. Al^{3+} meq/100g	0.10	ECR (mmol/L)	8.89
Aggregate stability (WS %	75	Exch.Ca^{2+} meq/100g	9.18	SAR (mmol/L)	0.22
Bulk density (g/cm^3)	1.08	Exch.Mg^{2+} meq/100g	2.82	ESP %	3.96
Hydraulic conductivity (mm/hr)	114	Exch.Na^{+} meq/100g	0.55	EPP %	8.80
Penetration resistance kg/cm^3)	0.41	Exch.K^{+} meq/100g	1.22	CROSS (mmol/L)	0.53
SOC %	2.29	ECEC (meq/100g)	13.87	pH (water)	6.00

5.3.4 Aggregate stability

The procedure by which aggregate stability was measured significantly influenced results. For the rainfall simulation procedure, average aggregate stability over the duration of the experiment was significantly higher than the control in the MPW+HG+LP, HPW+HP and MPW treatments by 37 %, 28 % and 39 % respectively. In contrast, for the wet sieving procedure, these same treatments were 24 %, 18 % and 22 % higher than the control, respectively (Table 5.5).

Differences in aggregate stability were also observed over time, for example, aggregate stability determined by rainfall simulation was significantly higher in the HP treatment

at four of the five sampling periods, whilst aggregate stability determined by wet sieving was not significantly different to the control at any the sampling date. In the LG, HG, WM+HG and LP treatments, none of the measure of aggregate stability was significantly different to the control at any of the sampling date.

Table 5.5. Aggregate stability determined by rainfall simulation and wet sieving at 8, 14, 28, 71 and 197 days after treatment application.

Treatments	Mean aggregate stability by rainfall simulation					Mean aggregate stability by wet sieving				
	Day 8	Day 14	Day 28	Day 71	Day 197	Day 8	Day 14	Day 28	Day 71	Day 197
Control	27.18	22.38	23.99	23.39	24.99	52.51	55.75	51.47	48.26	39.89
LG	31.81	28.87	28.54	26.68	26.21	61.00	57.52	56.64	53.37	38.97
HG	30.81	28.78	25.06	26.15	28.38	57.55	57.52	55.76	53.93	40.74
WM+HG	33.19	29.94	26.92	24.25		60.66	60.43	55.36	55.42	
LPW	35.31	35.21*	28.19	29.07	26.08	60.07	57.55	55.53	59.49*	42.02
MPW	41.75**	36.00*	31.78*	30.36*	29.73	67.63*	67.12*	58.06	62.81**	48.57
LP	30.51	28.72	24.95	23.76	24.68	55.07	57.53	51.85	48.85	39.95
HP	36.60*	34.32*	30.15*	30.27*	25.70	63.24	65.73	55.01	53.42	42.62
HG+LP	35.00	30.12	28.35	26.60	30.94*	59.96	59.29	56.34	57.96	48.43
MPW+HG-LP	38.58*	34.73*	33.01**	30.11*	30.12*	69.36**	65.41	62.00*	61.70*	49.49
HPW+HP	40.24**	37.46*	34.43**	34.41**	33.11**	68.03**	66.65*	64.20**	65.05**	50.54*

LG: 0.25 kg/m^2 gypsum, **HG:** 0.50 kg/m^2 gypsum, **LPW:** 1 kg/m^2 paper waste, **MPW:** 2.5 kg/m^2 paper waste, **LP:** 80 ml/m^2 H_3PO_4, **HP:** 160 ml/m^2 H_3PO_4, **WM+HG:** wire mesh+ 0.50 kg/m^2 gypsum, **HG+LP:** 0.50 kg/m^2 gypsum +80 ml/m^2 H_3PO_4, **MPW+HG+LP:** 2.5 kg/m^2 paper waste +0.50 kg/m^2 gypsum +80 ml/m^2 H_3PO_4, **HPW+HP:** 7.5 kg/m^2 paper waste+160 ml/m^2 H_3PO_4, ***** =significant P<0.05, ****** = significant P<0.01 (significant to the control), WM+HG: wire mesh was removed at day 71, and no measurements were conducted on day 197.

5.3.5 Surface density and hydraulic conductivity

In the control treatment, surface density increased from 1.08 g/cm^3 to 1.40 g/cm^3 between day 1 and day 8, to 1.50 g/cm^3 by day 197 (Table 5.6). Compared with the control, application of HPW+HP, MPW+HG+LP and HG significantly reduced surface density at all sampling dates by approximately 10 %, 7 % and 7 %, respectively, whilst LP, LPW, WM+HG and LG had no significant effect on surface density at any of the sampling dates. Application of HP and MPW significantly decreased surface density relative to the control at days 8 and 14 by 6 % and 9 % respectively, but had no effect on surface density on or after day 28. The HG+LP treatments significantly decreased surface density at days 14 and 28 by approximately 9 %, but not days 8, 71 and 197.

The effect of the treatments on hydraulic conductivity was less apparent than other measures of crust severity (Table 5.6). Relative to the control, the LG, HG, WM+HG and LPW treatments had no significant effect on hydraulic conductivity at any of the sampling date. The HPW+HP, MPW+HG+LP, HG+LP, HP, LH and MPW treatments resulted in significantly greater hydraulic conductivity (ranging from 64.0 to 88.5 mm/hr) compared with the control (37.1 mm/hr) at day 8. Moreover, the HPW-HP treatment significantly increased hydraulic conductivity compared with the control at day 14 (64.9 mm/hr versus 32.6 mm/hr) and at day 28 (30.1 mm/hr versus 15.9 mm/hr). By day 71 there was no significant difference in hydraulic conductivity between the control and any of the treatment.

Table 5.6. Bulk density and hydraulic conductivity of sandy clay loam after 8, 14, 28, 71 and 197 days of treatment application.

Treatments	Mean value of bulk density g/cm^3					Mean value of hydraulic conductivity mm/hr				
	Day 8	Day 14	Day 28	Day 71	Day 197	Day 8	Day 14	Day 28	Day 71	Day 197
Control	1.40	1.43	1.46	1.47	1.50	37.1	32.6	15.9	16.4	18.5
LG	1.34	1.38	1.46	1.46	1.44	45.6	32.9	19.9	16.4	22.1
HG	1.32*	1.34*	1.33***	1.36**	1.39*	48.0	47.1	18.7	25.0	24.5
WM+HG	1.35	1.39	1.47	1.48		57.7	41.3	27.8	29.8	
LPW	1.35	1.36	1.44	1.42	1.42	53.9	35.8	18.19	15.0	17.2
MPW	1.27**	1.31**	1.40	1.43	1.41	64.0*	44.0	21.7	23.4	26.2
LP	1.35	1.38	1.46	1.51	1.45	71.4**	42.51	23.04	20.2	21.3
HP	1.31**	1.35*	1.50	1.51	1.45	77.6**	47.6	18.1	19.1	22.0
HG+LP	1.34	1.34*	1.30***	1.40	1.44	67.4*	49.8	16.0	16.3	26.2
MPW+HG+LP	1.26***	1.31**	1.38*	1.40	1.39*	67.5*	62.7**	24.3	26.3	26.5
HPW+HP	1.22***	1.26***	1.29***	1.33**	1.37**	88.5***	64.9**	30.1*	27.7	27.6

LG: 0.25 kg/m^2 gypsum, **HG:** 0.50 kg/m^2 gypsum, **LPW:** 1 kg/m^2 paper waste, **MPW:** 2.5 kg/m^2 paper waste, **LP:** 80 ml/m^2 H_3PO_4, **HP:** 160 ml/m^2 H_3PO_4, **WM+HG:** wire mesh+ 0.50 kg/m^2 gypsum, **HG+LP:** 0.50 kg/m^2 gypsum +80 ml/m^2 H_3PO_4, **MPW+HG+LP:** 2.5 kg/m^2 paper waste +0.50 kg/m^2 gypsum +80 ml/m^2 H_3PO_4, **HPW+HP:** 7.5 kg/m^2 paper waste+160 ml/m^2 H_3PO_4, ***** =significant P<0.05, ****** = significant P<0.01, *** =significant P<0.001 (significant to the control), WM+HG: wire mesh was removed at day 71, and no measurements were conducted on day 197.

5.3.6 Penetration resistance

Penetration resistance increased during the trial period in all treatments (Table 5.7). Application of MPW+HG+LP and HPW+HP resulted in significantly lower penetration resistance than the control at all sampling dates. The penetration resistance of the HG+LP and HG treatments (average: 0.95 kg/cm^2 and 1.09 kg/cm^2 respectively) were significantly less than the control (1.43 kg/cm^2) during the first 71 days of the trial, while MPW significantly reduced penetration resistance for the period between 14 to 71 days by approximately 35 %. The LG treatment appeared to have a temporary effect on penetration resistance as it only reduced penetration resistance at day eight. The WM+HG, LPW and LP treatments had no significant effect on penetration resistance at any of the sampling date.

Table 5.7. Penetration resistance after 8, 14, 28, 71 and 197 days of treatment application.

Treatments	Mean value of penetration resistance kg/cm^2				
	Day 8	Day 14	Day 28	Day 71	Day 197
Control	1.05	1.28	1.38	2.02	2.41
LG	0.77*	0.94	1.03	1.70	1.73
HG	0.72*	0.94	1.00*	1.60*	2.03
WM+HG	0.96	1.09	1.14	1.75	
LPW	0.87	0.97	1.08	1.80	1.77
MPW	0.85	0.87*	0.95*	1.33**	1.61
LP	0.83	0.95	1.09	1.86	1.80
HP	0.78	0.94	1.04	1.77	1.97
HG+LP	0.56**	0.89*	0.98*	1.38**	1.72
MPW+HG+LP	0.65**	0.78*	0.92*	1.29**	1.53*
HPW+HP	0.48***	0.73**	0.87**	1.07***	1.15**

LG: 0.25 kg/m^2 gypsum, **HG:** 0.50 kg/m^2 gypsum, **LPW:** 1 kg/m^2 paper waste, **MPW:** 2.5 kg/m^2 paper waste, **LP:** 80 ml/m^2 H_3PO_4, **HP:** 160 ml/m^2 H_3PO_4, **WM+HG:** wire mesh+ 0.50 kg/m^2 gypsum, **HG+LP:** 0.50 kg/m^2 gypsum +80 ml/m^2 H_3PO_4, **MPW+HG+LP:** 2.5 kg/m^2 paper waste +0.50 kg/m^2 gypsum +80 ml/m^2 H_3PO_4, **HPW+HP:** 7.5 kg/m^2 paper waste+160 ml/m^2 H_3PO_4, ***** =significant P<0.05, ****** = significant P<0.01, ***=significant P<0.001 (significant to the control), WM+HG: wire mesh was removed at day 71, and no measurements were conducted on day 197.

5.3.7 Effect of soil amendments on selected chemical properties

One way ANOVA demonstrated that the MPW, HG+HP, MPW+HG+LP and HPW+HP treatments resulted in significantly higher average SOC, $Ca^{2+,}$ Al^{3+} and ECEC, and lower average Na^{+} and SAR compared with the control (Table 5.8). The low and high rates of phosphoric acid had no effect on selected soil properties other than SOC at the high rate. The high rate gypsum (HG) and WM+HG treatments significantly increased average Ca^{2+} and average ECEC compared with the control, but did not significantly influenced other soil chemical properties.

Table 5.8. Positive (+) and negative (-) effect of treatments on selected soil chemical properties compared with the control.

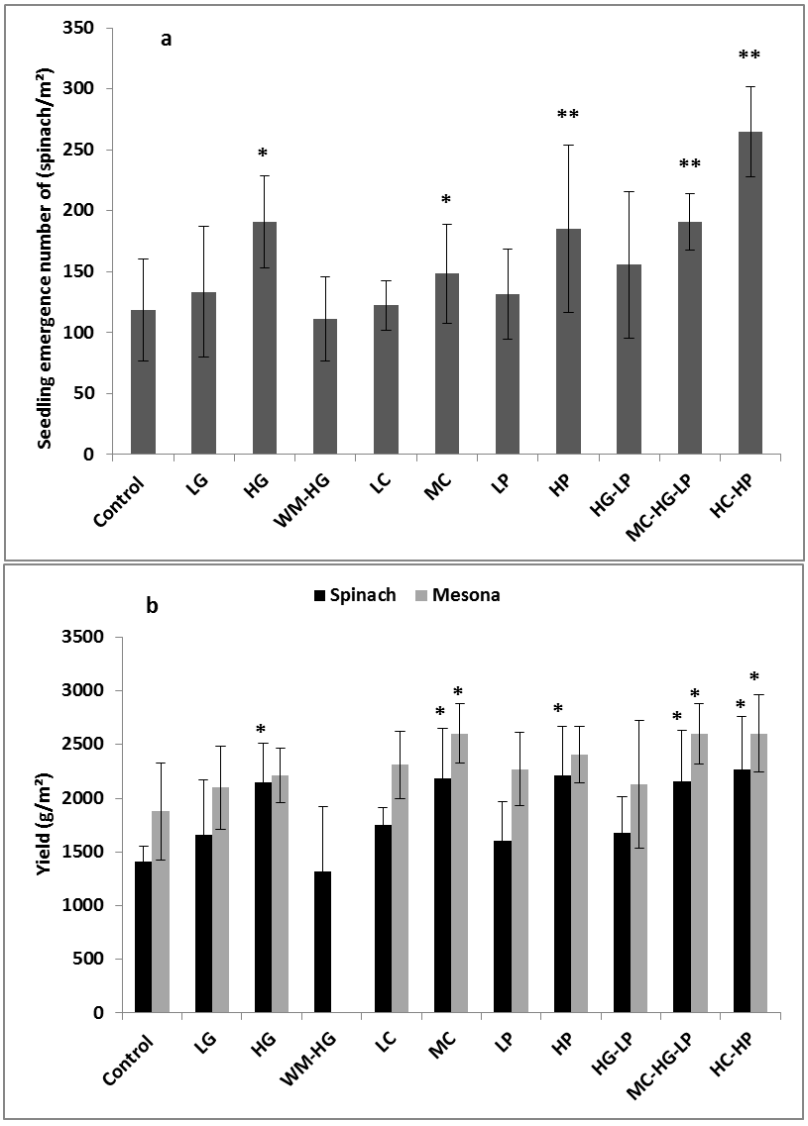
Treatments	SOC %	Exchangeable			Reactive Al^{3+}	ECEC (meq/100g)	SAR (mmol/L)	ESP %	pH
		Al^{3+}	Ca^{2+}	Na^{+}					
LG			++						
HG			+++	-		++	-	---	+
WM+HG			+++			++			
LPW	++								
MPW	+++		++	-	+	+	-	--	
LP									
HP	++								
HG+LP	++		+++			++	-	---	
MPW+HG-LP	+++	++	+++	-	+	+++	---	---	++
HPW+HP	+++	+	+++	-	++	+++	--	---	++

LG: 0.25 kg/m^2 gypsum, **HG:** 0.50 kg/m^2 gypsum, **LPW:** 1 kg/m^2 paper waste, **MPW:** 2.5 kg/m^2 paper waste, **LP:** 80 ml/m^2 H_3PO_4, **HP:** 160 ml/m^2 H_3PO_4, **WM+HG:** wire mesh+ 0.50 kg/m^2 gypsum, **HG+LP:** 0.50 kg/m^2 gypsum +80 ml/m^2 H_3PO_4, **MPW+HG+LP:** 2.5 kg/m^2 paper waste +0.50 kg/m^2 gypsum +80 ml/m^2 H_3PO_4, **HPW+HP:** 7.5 kg/m^2 paper waste+160 ml/m^2 H_3PO_4, **+/-** =significant $P<0.05$, **++/--** = significant $P<0.01$, +++/---=significant $P<0.001$ (significant to the control).

5.3.8 Crop production and seedling emergence

Application of HPW+HP, MPW+HG+LP and MPW significantly increased seedling emergence and yield of both spinach and mizuna (Figure 5.1). Application of HP and HG resulted in significantly higher seedling emergence and yield of spinach compared

with the control, while the yield of mizuna was not significantly influenced by HP or HG. No other amendments appeared to have a significant effect on seedling emergence or crop yield.



- LG: 0.25 kg/m^2 gypsum
- HG: 0.50 kg/m^2 gypsum
- LPW: 1 kg/m^2 paper waste
- MPW: 2.5 kg/m^2 paper waste
- LP: 80 ml/m^2 H3PO4
- HP: 160 ml/m^2 H3PO4
- WM+HG: wire mesh+ 0.50 kg/m^2 gypsum
- HG+LP: 0.50 kg/m^2 gypsum +80 ml/m^2 H3PO4
- MPW+HG+LP: 2.5 kg/m^2 paper waste +0.50 kg/m^2 gypsum +80 ml/m^2 H3PO4
- HPW+HP: 7.5 kg/m^2 paper waste+160 ml/m^2 H3PO4

*=significant difference to the control at P<0.05, **=significant difference to the control at P<0.01, WM+HG: wire mesh was removed at day 71, and no measurements were conducted on day 197.

Figure 5.1. Seedling emergence (a) and yield of spinach and mizuna (b) of sandy clay loam. Error bars indicate ±1 standard deviation.

5.3.9 Evaluation of soil amendments

Differences between the treatments and the control is summarised in the Table 5.9 to simplify comparison between treatments and measures of crust severity/likelihood. The LG, WM+HG, LPW and LP treatments had little to no influence on soil properties, yield or seedling emergence. The HG, HP and HG+HP treatments had moderate or occasional effect on most soil properties for at least one sampling date. The MPW, MPW+HG+LP and HPW+HP significantly influenced all soil properties for at least one sampling date, and improved seedling emergence and yield of both crops.

Table 5.9. Summary of effects of treatments on seedling emergence, yield and the number of sample dates in which a significant difference existed between the soil amendments and the control.

Treatments	Number of significant improvements compared to the control						Yield		Seedling emergence
	Rainfall simulation	Wet sieving	Bulk density	Hydraulic conductivity	Penetration resistance	Total	Spinach	Mizuna	
LG	0	0	0	0	1	1	No	No	No
HG	0	0	5	0	3	8	**yes**	No	No
WM+HG	0	0	0	0	0	0	No	No	No
LPW	1	1	0	0	0	2	No	No	No
MPW	4	3	2	1	3	13	**yes**	**yes**	**yes**
LP	0	0		1	0	1	No	No	No
HP	4	0	2	1	0	7	**yes**	No	No
HG+LP	1	0	2	1	4	8	No	No	No
MPW+HG+LP	5	3	4	2	5	19	**yes**	**yes**	**yes**
HPW+HP	5	5	5	3	5	23	**yes**	**yes**	**yes**

LG: 0.25 kg/m^2 gypsum, **HG:** 0.50 kg/m^2 gypsum, **LPW:** 1 kg/m^2 paper waste, **MPW:** 2.5 kg/m^2 paper waste, **LP:** 80 ml/m^2 H_3PO_4, **HP:** 160 ml/m^2 H_3PO_4, **WM+HG:** wire mesh+ 0.50 kg/m^2 gypsum, **HG+LP:** 0.50 kg/m^2 gypsum +80 ml/m^2 H_3PO_4, **MPW+HG+LP:** 2.5 kg/m^2 paper waste +0.50 kg/m^2 gypsum +80 ml/m^2 H_3PO_4, **HPW+HP:** 7.5 kg/m^2 paper waste+160 ml/m^2 H_3PO_4,

5.4 Discussion

5.4.1 Measurement of soil crusting

Analyses of soil crusting proved costly, time consuming and required use of specialised equipment. The moderate to high degree of correlation ($R^2 = 0.57 – 0.80$) between the different soil physical measurement suggests that the severity/likelihood of crusting could be measured using fewer procedures or even a single approach. The crust density approach had the lowest between treatment COV and as such relatively poor discrimination between treatments. The low COV of the crust density approach was attributed to difficulty in measuring crust thickness while sampling.

Hydraulic conductivity was the most time consuming procedure, which required greater skill to operate, yet had the highest COV or ability to discriminate between treatments. However, of the five methods the hydraulic conductivity procedure had the least discrimination between the control and treatments. Moreover, hydraulic conductivity was poorly correlated with the other approaches.

The penetration resistance procedure proved to be simple, rapid and had reasonable COV. Of the two measurements of aggregate stability, the rainfall simulation approach had higher between treatments COV, thus a greater capability to discriminate between treatments than wet sieving. However the rainfall simulation procedure was substantially slower than the wet sieving procedure.

5.4.2 Soil treatments

Three of the 11 treatments (MPW, MPW+HG+LP and HPW+HP) were observed at least one sampling date, in which all soil physical measures of crusting significantly differed from that of the control and had improved seedling emergence and crop yield. Other soil amendments varied in their effects on measured soil properties. The low rates

of gypsum, phosphoric acid and paper waste appeared to have no or little influence on the severity/likelihood of crusting, whilst the high rate of phosphoric acid appeared to reduce the severity of crusting in the critical 10 days following sowing when seedlings were emerging. The most effective amendments were paper waste and gypsum. Regardless of the significant improvement in soil crusting, all treatment developed sever crusting over the duration of the trial. The effect of each product and product combination is discussed in the following suctions.

5.4.2.1 *Gypsum*

Gypsum (LG) applied at 0.25 kg/m^2 had no significant effect on soil physical properties, seedling emergence, crop yield, exchangeable Na^+, SAR or ESP. The only significant effect of the LG treatment was on penetration resistance at one sampling date. In contrast, the high rate of gypsum (HG) significantly reduced bulk density at all five sampling dates, and penetration resistance at three of the five sampling dates. Relative to the control, the HG treatment also significantly increased the yield of spinach, but not the mizuna, whilst having no effect on emergence of the spinach. Moreover, the HG treatment had no significant effect on aggregate stability or hydraulic conductivity at any of the sampling date. Chemical analysis demonstrated that the HG treatment resulted in significantly higher average exchangeable Ca^{2+}, ECEC and pH, and significantly decreased average exchangeable Na^+ and the ratio of monovalent to polyvalent cations compared to the control. Similar to our findings, Scotter and Loveday (1966) reported that total porosity increased in non-sodic soils (ESP <6) when treated with gypsum through reduced dispersion and increased flocculation. Agassi et al. (1981) suggested that gypsum promoted aggregation by provision of exchangeable Ca^{2+} and reduced clay swelling, resulting in increased aggregate stability and reduced soil crusting.

5.4.2.2 *Paper waste*

Application of paper waste at 1.0 kg/m^2 (LPW) had minimal effect on severity/likelihood of crust formation. The LPW treatment had no significant effect on any measure of crust severity/likelihood, seedling emergence or crop yield (other than aggregate stability for one sampling date). Application of paper waste at the moderate rate of 2.5 kg/m^2 (MPW) significantly improved all measured soil properties for at least one sampling date. The MPW treatment also significantly increased seedling emergence and crop yield of both spinach and mizuna.

Chemical analysis of the treated soil indicated that application of MPW significantly increased average SOC, ECEC and exchangeable Ca^{2+} and Al^{3+}, and decreased average exchangeable Na^{+} and the proportion of monovalent to polyvalent cations. The paper waste was likely to have reduced crust severity/likelihood due to a combination of (i) the low density of the paper waste (0.11 g/cm^3) compared to the soil (1.08 – 1.50 g/cm^3) (Table 1); (ii) the slow wettability of the paper waste, which may have reduced the air compression and clay swelling in the surrounding soils as observed by Leelamanie et al. (2013) and Sullivan (1990); (iii) decomposition resulting in release of organic cementing compounds such as polysaccharides (Tisdall & Oades 1982, Chaney & Swift 1984) and (iv) the high level of available Ca^{2+}, which is likely to have displaced Na^{+} on the exchangeable clays and thus potentially reduced clay dispersion and promoted flocculation. These finding is in agreement with other studies that demonstrated that application of organic materials improved soil aggregation and soil structure including improvements in aggregate stability, bulk density and infiltration (Tisdall & Oades 1982, Haynes 2000, Carter 2002).

5.4.2.3 *Phosphoric acid*

Application of phosphoric acid at 80 mls/m^2 (LP) had no significant effect on the measured soil physical properties except hydraulic conductivity at day 8, seedling emergence or crop yield. However, application of phosphoric acid at 160 mls/m^2 (HP) significantly improved aggregate stability determined by rainfall simulation (4 of 5 sampling dates), crust density (2 of 5 sampling dates) and hydraulic conductivity (1 of 5 sampling dates), whilst the HP treatment had no significant effect on aggregate stability determined by wet sieving, penetration resistance, seedling emergence or crop yield. The HP treatment was observed to have a greater effect on soil physical properties in the first three to four sampling times.

Chemical analysis demonstrated that the HP treatment significantly increased SOC compared with the control, however no other significant effects were observed. Udom and Ogunwole (2015) also reported that improvement of aggregate stability by application of phosphorus fertilizers was associated with increased SOC.

5.4.2.4 *Treatment combinations*

The wire mesh and high rate of gypsum (WM+HG) were not effective at preventing crusting. It was thought that the combination of wire mesh as a physical means to reduce raindrop impact and the high rate of gypsum to prevent dispersion and encourage flocculation would act together to reduce surface crusting. However, the WM+HG treatment had no significant effect on any measure of crust severity/likelihood at any of the sampling date. Moreover, the WM+HG negatively influenced seedling emergence and yield, which was attributed to wire acting as a barrier to seedling emergence.

The combination of 0.50 kg/m^2 gypsum and 80 mls/m^2 phosphoric acid (HG+LP) had similar results to that of the HG alone. The HG+LP treatment appeared to be an

effective means of reducing soil crusting in the early sampling times as it significantly reduced penetration resistance prior to day 197, and crust density at day 14 and day 28. Results for the HG+LP treatment indicate that the phosphoric acid did not make a substantial contribution to improving the measured soil properties, although a significant increase in average SOC was noted. The early beneficial effect of HG+LP treatment may result from gypsum contribution by providing exchangeable Ca^{2+}, leading to increased aggregating agents.

The combination of high application of paper waste (7.5 kg/m^2) and phosphoric acid (160 mls/m^2) (HPW+HP) was the most effective treatment for reducing the severity and likelihood of crusting. The HPW+HP treatment significantly improved all soil physical properties relative to the control for at least three of the five sampling dates. The HPW+HP treatment also influenced all measured soil chemical properties including significantly increasing average values of organic matter, pH (H_2O), ECEC and exchangeable polyvalent cations (Ca^{2+}, Al^{3+}), whilst significantly decreasing average exchangeable Na^{+}. Comparison of results for HPW+HP and HP indicate that the phosphoric acid made only a minor contribution to the increased performance of HPW+HP treatment compared with the high rate of paper waste (HPW) alone.

The combination of the moderate rate of paper waste (2.5 kg/m^2), high rate of gypsum (500g/m^2) and low rate of phosphoric acid (160 mls/m^2) (MPW+HG+LP) improved all measured soil physical properties. Relative to the control, the MPW+HG+LP treatment significantly increased the average SOC and ECEC, and significantly reduced average exchangeable Na+ and the ratio of monovalent to polyvalent cations. The MPW+HG+LP treatment also significantly increased seedling emergence and the yield of spinach and mizuna.

5.5 Conclusion

For routine measurement of crust severity, penetration resistance measured by pocket penetrometer was found to produce a good balance between precision and ability to discriminate between treatments, whilst being relatively inexpensive and quick to perform. Hydraulic conductivity proved to be the most time consuming and difficult procedure, whilst being poorly correlated with the other approaches. We recommended the use of penetration resistance for routine measurement of crust severity between treatments provided soils are of similar moisture content. For measurement of aggregate stability, the rainfall simulation procedure had greater ability to discriminate between treatments than wet sieving. However, the rainfall procedure was time consuming and resulted in fewer significant differences between treatments and the control.

The severity/likelihood of crusting was significantly reduced compared with the control by the HPW+HP, MPW+HG+LP, MPW, HP and HG treatments. Paper waste was the most effective single amendment followed by gypsum. Phosphoric acid was also found to be effective means of reducing crusting in the two weeks after sowing (8 – 14 days). Therefore, it is considered that phosphoric acid may have the ability to reduce soil crusting during the critical 10 days following sowing when seedling emergence occurs. However, repeated use of phosphoric acid will have implications for crop nutrition.

No one amendment or combination of amendments prevented the development of severe soil crusting at the site. For example, for the most effective treatment HPW+HP, bulk density increased from 1.08 g/cm^3 prior to rainfall /irrigation to 1.37 g/cm^3 on day 197, whilst hydraulic conductivity still decreased from 113.7 to 27.6 mm/hr over the same period. For management in packet salad, results indicate that gypsum and phosphoric acid should be added to the soil prior to sowing due to the short duration of

their effects. In contrary, paper waste should be added to soil periodically i.e. yearly to help maintain soil quality.

Next chapter

Although some of the evaluated amendments were shown to significantly reduce soil crusting compared to the control in Chapter 5, no single amendment prevented crust formation. The effect of soil crusting on soil hydrology, the density, penetration resistance, hydraulic conductivity, instability, hydrology and cracking pattern were monitored over a 71 day period in Chapter 6.

Chapter 6: Quantifying the physical and hydrological properties of soil crusts

Abstract

Soil crust formation results in considerable modification in soil hydrological properties. The aim of this Chapter is to determine (i) the change in the degree of crust formation over time, (ii) the effect of soil crust formation on soil porosity and water movement, and (iii) determining hydrological properties of soil crusts required for modelling. Measurements included crust density, penetration resistance, unsaturated hydraulic conductivity by minidisk infiltrometer and tension infiltrometer, and steady state infiltration from droplets falling from 2 cm and 120 cm height. Measurements were conducted on day 1, 8, 14, 28 and 71 after cultivation on a sandy clay loam southern Tasmania, Australia. Crust porosity was determined using scanning electron microscopy (SEM) for crust collected on day 71. The water retention curve for the soil crust at high matric potential was determined using dew point potential meter (WP4C). The inverse solution of infiltration data from minidisk infiltrometer using HYDRUS 2D/3D and RETC models was used to estimate Van Genuchten parameters, and thus predict water retention curve. Results indicated that crust formation had mostly occurred by day 14. Results of the WP4C indicated that no significant difference existed in the water retention curve between crusted and non-crusted soil. The SEM images indicated that the soil a crust consisted of a 290 µm thick upper layer with approximately 3.5 % porosity over an 1800 µm thick layer with 15 % porosity, in which the pore size in the surface layer was between 40 µm and 250 µm. As crusts formed, steady state infiltration rate from droplets falling from a height of 2 cm decreased from 474 mm/hr prior to crust formation to 33 mm/hr by day 71. The measured value of saturated hydraulic conductivity determined from minidisk and Cornell infiltrometer at day 71 was similar

to that estimated from HYDRUS 2D/3D and RETC ranging from 8.5 mm/hr to 17 mm/hr. Difficulty was encountered with estimating of the θ_s, and α van Genuchten parameters.

6.1 Introduction

Soil crusting results in considerable modification to the physical properties of the soil surface (Algayer et al. 2014). These modifications include reduced porosity and reduced infiltration and hydraulic conductivity, which cause increased runoff and erosion (Agassi et al. 1985, Sumner & Miller 1992, Fox et al. 2004). In addition, crusting forms a physical barrier to seedling emergence, resulting in reduced crop yield (Awadhwal & Thierstein 1985). The extent to which crusts form, and their impact on water movement and seedling emergence, varies according to soil type, surface conditions and rainfall characteristics (Fox et al. 2004, Carmi & Berliner 2008). Despite the potential importance of surface crusting on soil hydrology and crop establishment, little is actually known about the hydrological properties of soil crusts. This is in part due to their fragile nature which makes routine measurement difficult (Pulido et al. 2014).

The effect of crust formation on a range of soil properties including infiltration rate, porosity and bulk density have been reported previously. For example, Jakab et al. (2013) reported that the infiltration rate of crusted soil was around three times lower than that for non-crusted soil, resulting in decreased surface water storage and increase runoff. Souza et al. (2014) reported that the time required for infiltration to reach 113 mm depth ranged between 1140 to 2880 seconds for crusted soil, compared to only 400 to 670 seconds for non-crusted soil. Yonter and Yagmur (2011) determined soil loss from a simulated rainfall experiment, in which rainfall event on the first non-crusted soil resulted in 276.52 g/m^2 to 100.44 g/m^2 soil loss, while the second event on crusted

soil resulted in 701.76 g/m^2 to 243.61 g/m^2 soil loss. Soil loss by the second event was attributed to crust formation and the reduction in water movement.

Few attempts have been made to incorporate surface soil crusting routines in soil water or crop models. Models such as APSIM and CERES use USDA runoff curve numbers to partition rainfall into runoff verses infiltration in which a crust like effect is invoked by multiply rainfall by a value less than 1 for one of four different surface soil textures. This approach is overall simplistic and ignores spatial and temporal variability of infiltration associated with crusting (Ponce & Hawkins 1996).

Nciizah and Wakindiki (2015) reported that despite some models having been modified to include soil crusting, 'no models adequately consider soil crusting'. The possible exception is the one dimensional Richard equation based model SWIM, in which crusting is invoked when surface water ponding develops (Verburg et al. 1996, Huth et al. 2012). Soil crusting is simulated via a surface conductance function, in which an infinite thin membrane is applied to the soil surface through which the water flux is determined by multiplying the surface conductance by the matric potential difference across the crust.

Improved knowledge of the hydrological properties of soil crusts and mechanisms by which they form are required to improve simulation of infiltration and soil water movement in crop-soil-water models. Development of crust routines in soil water models has to date been limited by a lack of data on the hydraulic characteristics of soil crusts and their rates of formation. The aim of this study is to (i) determine the changes in surface soil hydrological properties over time, (ii) determine the effect of soil crusting on infiltration and water movement, and (iii) evaluate approaches for measuring hydrological properties of soil crusts for future modelling.

6.2 Material and methods

6.2.1 Site description

As described in Chapter 5.2.1, the experiment was conducted on a commercial packet salad farm in the Coal River Valley in southern Tasmania (42.72532^{o} South, 147.43182^{o} East) (Plate 6.1). The climate was defined as a cool temperate with 500 mm of annual rainfall, yearly mean maximum temperature range of 12 – 22 ^{o}C and mean minimum temperature range of 4 – 12 ^{o}C (Bureau of Meteorology 2015). The soil was classified as a Brown Chromosol derived from Tertiary – Quaternary sediments with a tin capping of Aeolian sands and silts. The soil surface (0 – 5 cm) is slightly acid (pH = 6), non-sodic with an ESP of 3.96 %, moderate carbon of 2.3 %, which contains 55.9 % sand, 10.8 % silt, and 33.3 % clay and a cation exchange capacity (ECEC) of 13.9 meq/100g soil.

Measurements were conducted on a fallow bed after having been rotary hoed, as typically practised prior to sowing. Over the 28-day trial period, the site received 18 rainfall or irrigation events, between day 1 and 8 was 4 events, between day 8 and 14 was 5 events, and between day 14 and 28 was 9 events.

Plate 6.1. Field experiment site located in Coal River Valley, Southern Tasmania, Australia. Note severe crusting in fallow beds exposed to rainfall, and accumulation of sediments in the furrows.

6.2.2 Crust density

As described in Chapter 4.2.2, surface soil density was measured using the water replacement procedure (Plate 6.2), described by Cresswell and Hamilton (2002). A thin plastic bag was placed within level a 200 mm diameter ring, which was then filled with water to a known datum. The bag was removed and the soil crust was removed by scraping and portable vacuum. The water filled bag was then replaced on the soil surface and refilled to the original datum. Density was calculated by oven dry mass of the excavated soil divided by the volume of water required to return to the datum. Crust density was measured in triplicate on day 1, 8, 14, 28 and 71.

Plate 6.2. The water replacement apparatus used for measuring crust density.

6.2.3 Penetration resistance

As described in Chapter 4.2.2, penetration resistance of the soil crust was measured using a CL-700 Pocket Penetrometer (kg/cm^2), in which 10 replicates were taken in each plot. Measurement of penetration resistance was conducted on days 1, 8, 14, 28 and 71.

6.2.4 Hydraulic conductivity

Hydraulic conductivity was determined by infiltration from both a mini disk infiltrometer (Decagon, version 10) (Plate 6.3) and a 200 mm diameter tension infiltrometer with a detached reservoir (Plate 6.4). Suction heads of -6, -5, -4, -3, -2 and -0.5 cm were applied with the mini disk infiltrometer and -15, -10, -6, -3, -1 and -0.5 cm for the tension infiltrometer. The initial water content in the surface layer and final water content below the tension infiltrometers was measured using a Decagon EC5 probe. Unsaturated soil hydraulic conductivity was calculated according to Ankeny et al.

(1991), which assumed that the sorptive number (α) in the Gardner equation was constant over the interval between two adjacent supply pressure heads. Measurements were conducted in triplicate on day 1, on day 8, on day 14, on day 28 and on day 71.

Plate 6.3. The mini disk infiltrometer for measuring water infiltration at day 1. Note use of folder to prevent movement of the devices by wind, and coarse non-crusted nature of the soil surface.

Plate 6.4. Tension infiltrometer with offset reservoir for measuring water infiltration and unsaturated hydraulic conductivity at day 1.

6.2.5 Cornell sprinkler infiltrometer

Steady state infiltration was measured using a Cornell sprinkler infiltrometer mounted at 2 cm and 120 cm height above the soil surface (Plate 6.5 and 6.6). Measurements were conducted for 20 minutes for each of four replicates on days 1, 8, 14, 28 and 71. Flow rate from the infiltrometer was adjusted by lowering and raising the air entry tube and by shutting off flow in order that the surface was only allowed to form thin film (as indicated by glistening), whilst preventing runoff from the 314 cm^2 area under the drippers. Saturated hydraulic conductivity at 2 cm on day 71 was calculated based on Reynolds and Elrick (1990), for comparing with other measurements of saturated hydraulic conductivity. We assumed α to be 0.06 and tension head at 2 mm, with no ring insertion, initial moisture of 0.10 cm/cm and final moisture of 0.22 cm/cm.

Plate 6.5. Measurement of steady state infiltration by the Cornell sprinkler infiltrometer mounted at 120 cm above the soil surface at day 1. Note the person observing the level of ponding on the soil surface.

Plate 6.6. Measurement of steady state infiltration by Cornell sprinkler infiltrometer at 2 cm height above the crusted soil surface at day 8.

6.2.6 Retention curve using dew point potential meter (WP4C)

The fragile nature of moist soil crusts prevents determination of their retention function by traditional suction table and pressure chamber methods. A number of soil crusts were collected at day 71 for determination of soil water retention function by the WP4C. The WP4C is a dew point hygrometer, which uses a chilled mirror inside a sealed chamber (Leong et al. 2003), to determine the water potential according to the psychometric law (Fredlund & Rahardjo 1993). The absolute temperature (T) and the relative humidity (RH) are related to the total suction as below (Equation 6.1)

$$h = \frac{\rho_w RT}{M_w} ln(RH) \quad \ldots\ldots\ldots\

Science Laboratory, University of Tasmania. Images were analysed for crust thickness, porosity and pore size using Photoshop (CS3) and Image J (Schneider et al. 2012). Obvious debris and pore sidewalls were manually removed from the images using Photoshop (CS3). The measure tool in Image J was used to measure the thickness of crust layer and pore size. Images were converted to binary bases in Image J, in which soil pores were black (value 255) and the soil matrix white (value 0). The percentage of the non-pore area and soil porosity were determined using the analyse particle function in Image J.

6.2.8 Crust formation and cracking

A rigid frame (1.25 m x 1.00 m) was installed on the soil surface after preparing the beds for cultivation on day 1 (before sowing) to monitor the development of soil crusting and cracking over time (Plate 6.7). Digital images were captured on day 1, 8, 14, 28, and 71. Images were corrected for lens barrel distortion and key stone distortion in Photoshop (CS3). Images were imported to GIMP (version 2.8), in which the paintbrush tool was used to draw over the cracks in a separate layer in which the paintbrush thickness was matched to the crack width. The crack width and size of crust sections were determined using the measure tool in GIMP. The crack area was determined in Image J after conversion of the traced crack layer to binary format in Image J.

Plate 6.7. Rigid frame installed to monitor and photograph soil crusting over 71 days, image day 1.

6.2.9 Determination of soil water retention function by inverse solution using HYDRUS

Models of Van Genuchten (1980) and Mualem (1976) were used in HYDRUS 2D/3D to estimate water retention curve parameter values and saturated hydraulic conductivity using the inverse solution of infiltration data from the minidisk infiltrometer at seven tension steps based on the procedure described by Simunek et al. (1998). The flow domain was modified to allow for smaller minidisk size (45 mm), such that the flow domain contained 1416 nodes, with refinement near soil surface of 2 cm. In order to account for variation in infiltration between replicates, the average infiltration rate was calculated for each tension step. All data were equally weighted by a factor of 1, with exception of final moisture, which was weighted by a factor of 10. Parameter values were initially estimated, in which the θ_s parameter was estimated from the final moisture content under the minidisk infiltrometer at – 0.5 cm tension, as we considered the total porosity calculated from the crust density and SEM were inaccurate. The θ_r

was estimated from the WP4C values between 10000 and 500000 cm, while initial α, and *n* were estimated based on typical values for sandy clay loam soils provided in HYDRUS 2D/3D. The pore connectivity parameter (l) was assumed to be 0.5 to reduce the number of variables in the objective function. The van Genuchten model (VGM) parameters (θ_s, θ_r, α, *n*, K_s) were estimated simultaneously by numerical inversion in which initial estimates of the parameters were iteratively improved during the minimisation process until a desired precision was obtained (Ramos et al. 2006). The R^2 values for the estimation of VGM parameters were greater than 0.98.

6.2.10 Estimation of retention values by RETC

The RETC code was used to describe the hydraulic properties of the soil surface by fitting the values of VGM parameters (α, *n* and Ks) to the analytical model. The paired unsaturated soil hydraulic conductivity verses suction head data at -6, -5, -4, -3, -2 and -0.5 cm for each of the five measurement dates were used to estimate VGM parameters. The maximum number of iterations was set at 50. Initial values of α, *n* and Ks were estimated according to RETC recommendations for sandy clay loams. The R^2 values of the VGM parameters fitted hydraulic conductivity retention function K(ψ) was greater than 0.98.

6.2.11 Soil moisture

EC-5 soil moisture sensors were installed at the experiment site in the vertical and horizontal position at day 1 to monitor the volumetric water content of the soil between 0-2 cm depth. Soil moisture content sensors were removed from the site at day 30.

6.2.12 Statistical analysis

The influence of time on crust density, penetration resistance, hydraulic conductivity and steady state infiltration was explored using One-Way Analysis of Variance

(ANOVA) in SPSS (version 21). Differences in steady state infiltration between the two droplet formation heights, and differences in unsaturated hydraulic conductivity at different suction heads for both the minidisk infiltrometer and tension infiltrometer were determined using T-tests in in SPSS (version 21). Pearson correlation was used to determine the correlation between time and soil moisture for crack width, crack area and size of crust segment.

As the WP4C generates unique matric potential verses gravimetric moisture content data pairs, statistical analysis between the crusted and non-crusted soil required data to be fitted using a logarithmic function ($R^2 > 0.96$). From this, gravimetric water content was determined at – 10000 cm, – 20000 cm, – 50000 cm, – 100000 cm, – 200000 cm and – 500000 cm matric potentials for each sample. Statistical analysis was thus based on the fitted, rather than measured data pairs, which is acknowledged to have reduced variance between replicates. The fitted WP4C data was explored using One-Way Analysis of Variance and T-test in SPSS (version 21).

6.3 Results

6.3.1 Rainfall events

Soil moisture monitoring between 0 – 2 cm indicated that between day 1 and day 8 there were 4 irrigation or rainfall events, between day 8 and 14 there were 5 irrigation or rainfall events and 9 irrigation events between day 14 and day 28 (Figure 6.1). No data were received between day 28 and 71. Maximum soil moisture after irrigation (red line) tended to decrease with time after day 5, whist the soil moisture content after drainage (black line) tended to increase or remain constant after day 5. Both lines appeared to increase between day 1 and day 5.

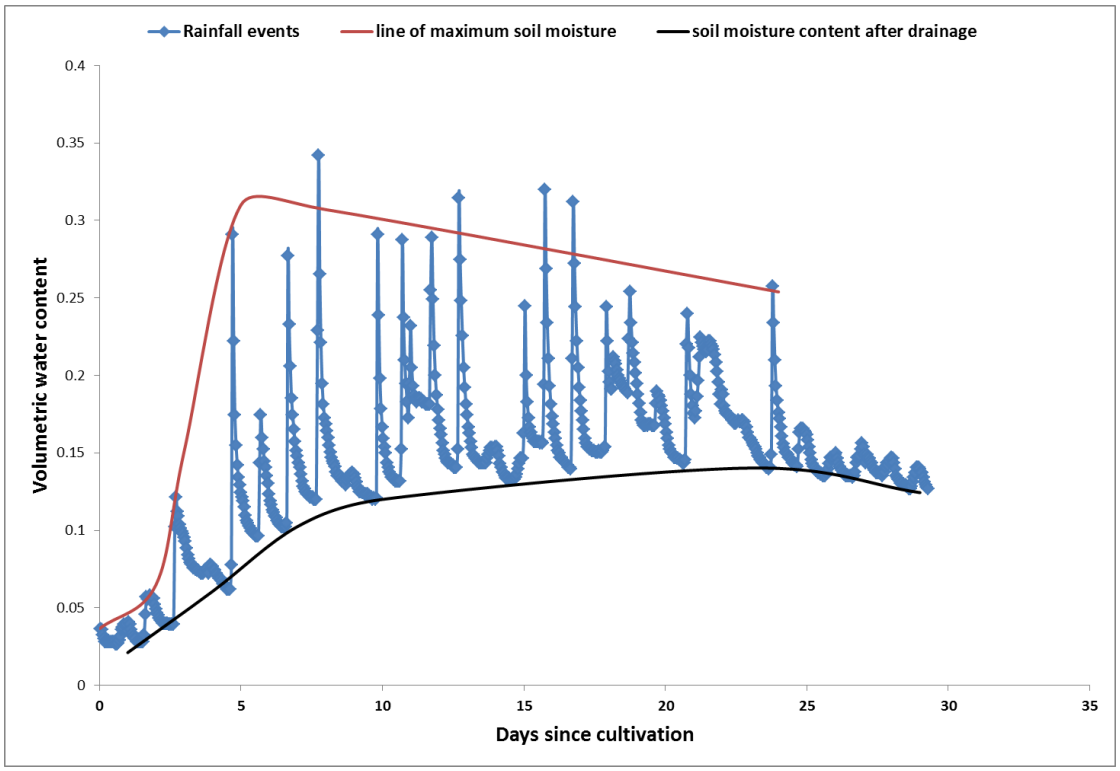


Figure 6.1. Change in soil moisture in response to rainfall and irrigation from day 1 to day 28 at a depth 0 – 5 cm. Note not all irrigation events were of equal duration.

6.3.2 Crust density and penetration resistance

The mean penetration resistance and surface density at day 1 were significantly lower than at all later measurement dates (Figure 6.2). Penetration resistance significantly increased from 0.31 kg/cm^2 at day 1, to 1.05 kg/cm^2 at day 8, and to 1.44 kg /cm^2 by day 71. No significant differences existed in the penetration resistance between days 14 and 71.

Crust density significantly increased from 1.17 g/cm^3 at day 1, to 1.46 g/cm^3 at day 14, and to 1.51 g/cm^3 by day 71. Crust density at day 14 was significantly higher than that at day 1 and 8, while no significant difference existed in crust density between day 14 and day 28, or 71.

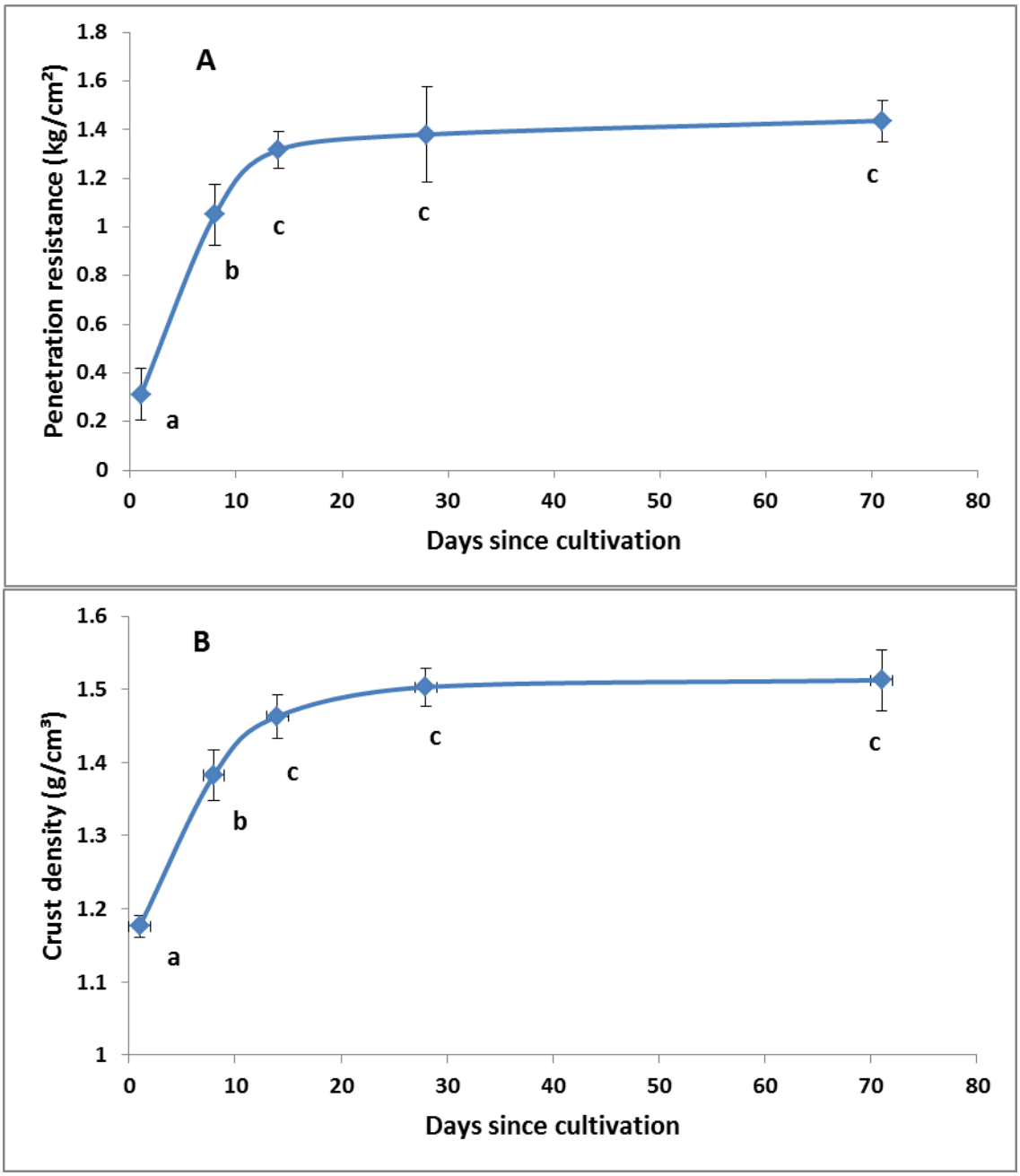


Figure 6.2. Change in penetration resistance (A) and crust density (B) over time in response to irrigation or rainfall events in Figure 1. Bars indicate ±1 standard error.

6.3.3 Hydraulic conductivity (mini disk)

6.3.3.1 *Comparison between trial dates*

For all suction heads, unsaturated hydraulic conductivity was at a maximum at day 1 then significantly decreased by day 14. For suction heads between – 6 cm to – 4 cm, no significant differences existed in unsaturated hydraulic conductivity between day 14 and

day 71. For suction head of -3 cm and – 2 cm, unsaturated hydraulic conductivity at day 14 was significantly higher than that at day 71, but not day 28. For suction head of – 1 cm and – 0.5 cm, unsaturated hydraulic conductivity significantly decreased at each measurement date (Figure 6.3).

6.3.3.2 *Comparison between suction heads*

Unsaturated hydraulic conductivity at a suction head of – 0.5 cm was significantly higher than that at a suction head of – 1 cm, which was significantly higher than the suction head at – 2 cm (days 1, 8, 14 and 28). Unsaturated hydraulic conductivity at a suction head of – 2 cm was significantly higher than that at a suction head of – 3 cm at days 1 and 8. No significant difference existed in the unsaturated hydraulic conductivity between suction heads at – 3 cm, - 4 cm, - 5 cm and – 6 cm at days 14 and 71 (Figure 6.3).

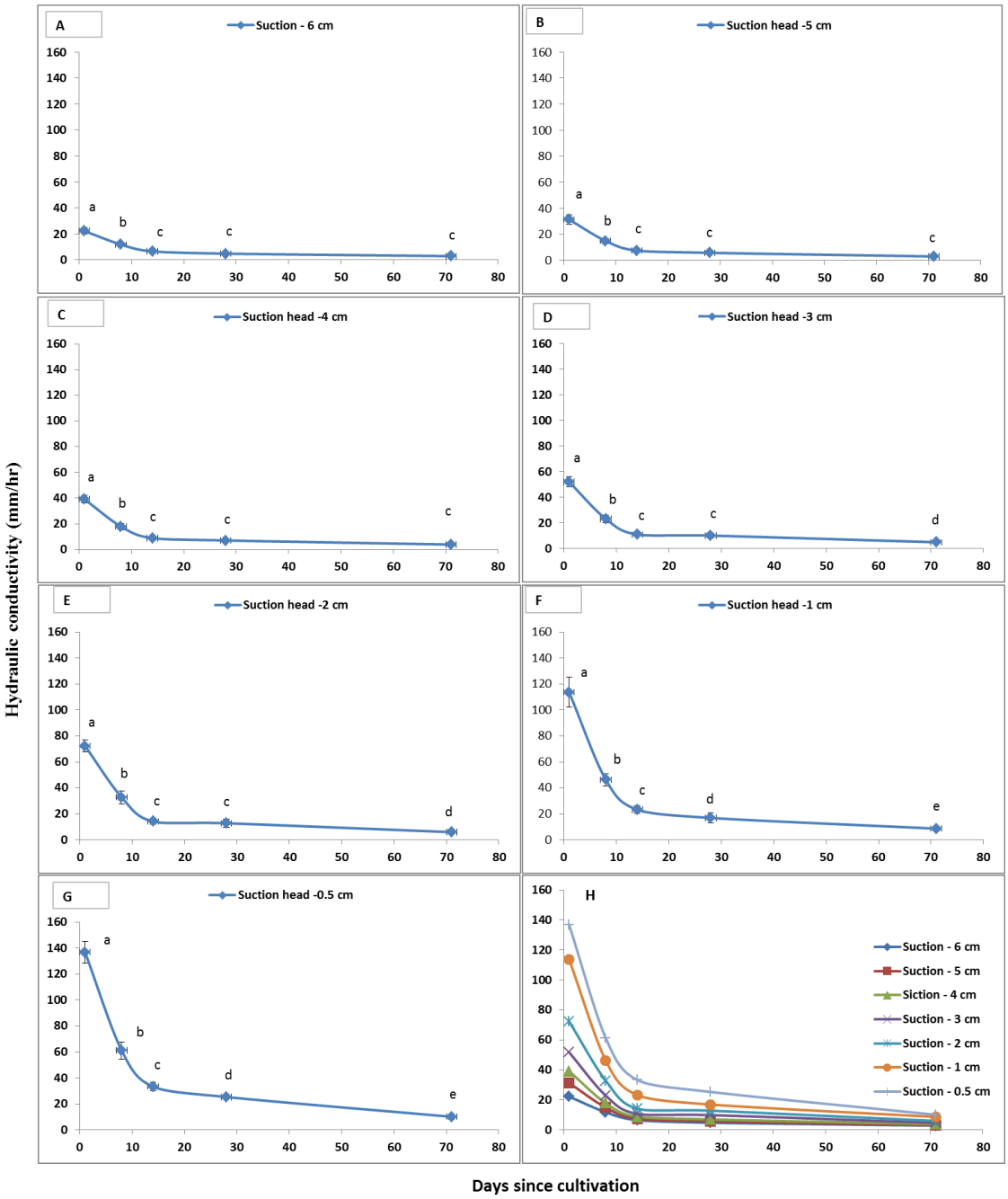


Figure 6.3. Values of unsaturated hydraulic conductivity at suction head (cm) - 6 (A), - 5 (B), - 4 (C), - 3 (D), - 2 (E), - 1(F), - 0.5(G) and combined of different suction (H) during the period between day 1 and day 71. Error bars indicate ±1 standard error.

6.3.4 Hydraulic conductivity (tension infiltrometer)

6.3.4.1 *Comparison between trial dates*

The unsaturated hydraulic conductivity verses the six suction heads over time is shown in Figure 6.4. For a suction head of – 15 cm and – 10 cm, the unsaturated hydraulic conductivity at day 1 was significantly higher than that at day 14, but not day 8. Contrary to the suction head at – 15 cm, no significant difference existed in the unsaturated hydraulic conductivity at suction head of – 10 cm between day 14 and day 71. For suction heads – 6 cm, and – 3 cm, unsaturated hydraulic conductivity at day 1 was significantly higher than that at day 8, which was significantly higher than that at day 14, whilst no significant differences existed between the unsaturated hydraulic conductivity at 14 and 28. For suction head of – 1 cm and – 0.5 cm, the only significant difference existed between day 1 and day 8.

6.3.4.2 *Comparison between suction heads*

For days 1 and 8, the unsaturated hydraulic conductivity at a suction head of – 0.5 cm was significantly higher than that at a suction head of – 1 cm, which was significantly higher than that at a suction head of – 3 cm. For days 14 and 28, unsaturated hydraulic conductivity at suction head – 0.5 cm was significantly higher than that at a suction head of -3 cm, whilst unsaturated hydraulic conductivity at a suction head of – 1 cm was higher than that at a suction head of – 6 cm. No significant differences existed in the unsaturated hydraulic conductivity between the suction head of – 3 cm and – 15 cm at day 1, 8, 14 and 28. For day 71, unsaturated hydraulic conductivity at a suction head of – 0.5 cm was significantly higher than that at a suction head of – 3 cm, which was significantly higher than that at a suction head of – 6 cm, whilst no significant differences existed between the suction head – 6 cm and – 15 cm.

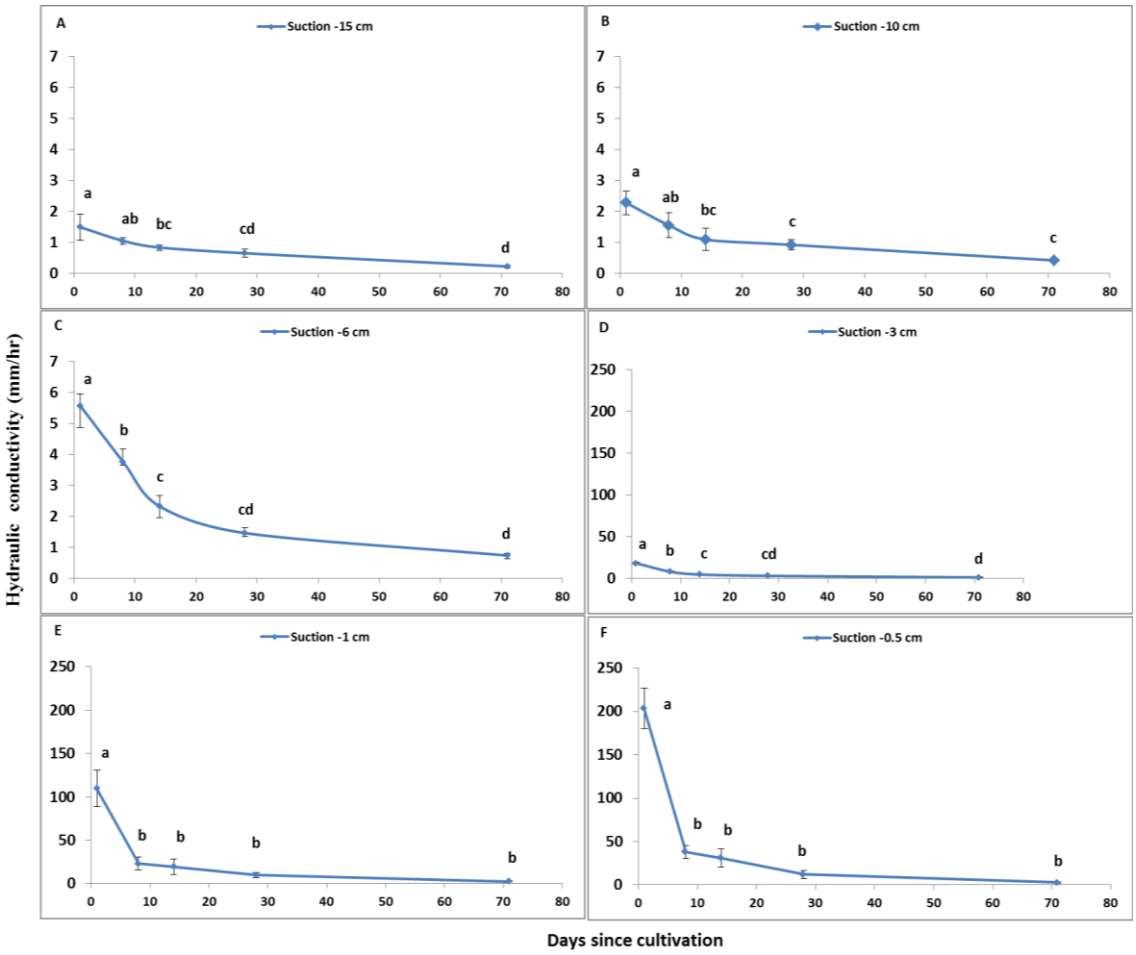


Figure 6.4. Values of unsteady state infiltration rate at suction head - 15 cm (A), - 10 cm (B), - 6 cm (C), -3 cm (D), - 1 cm (E) and - 0.5 cm (F) during the period between day 1 and day 71. Bars indicate ±1 standard error.

6.3.5 Infiltration rate with different energies

Between day 1 and day 28, the steady state infiltration rate for droplets falling from 120 cm height was significantly less than droplets falling from 2 cm height (Figure 6.5). However, no significant difference existed in the steady state infiltration rate between the two heights at day 71. For droplets falling from 2 cm height, steady state infiltration at day 71 was significantly lower than that at day 28, whilst no significant differences existed in the steady state infiltration during the period between day 8 and day 28. For droplets falling from 120 cm height, no significant difference existed in the steady state infiltration rate between day 8 and day 71.

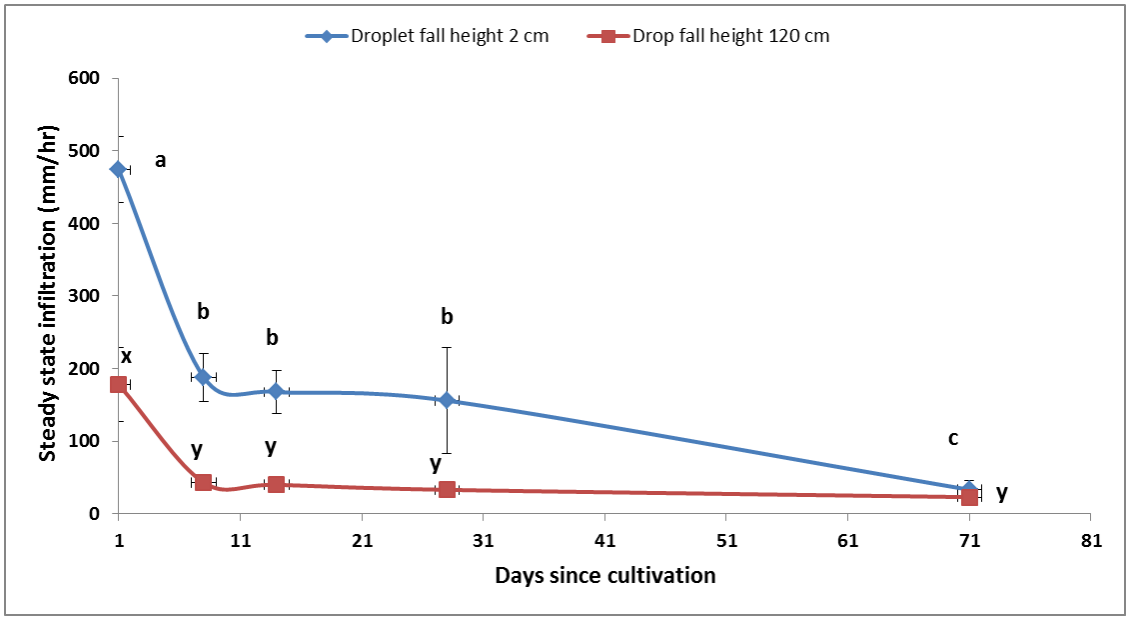


Figure 6.5 Change in steady state at infiltration rate at 2 cm and 120 cm height on days 1 (a), 8 (b), 14 (c), 28 (d) and 71 (e). Bars indicate ±1 standard error.

6.3.6 Water retention curve

The retention curves for crusted and non-crusted soils were presented as gravimetric water content due to difficulty determining volumetric moisture content of soil crusting (discussed in section 6.4.6). The water retention curve obtained by the WP4C from the soil crusts and disturbed soil beneath the crust collected on day 71, shows there was no

significant difference in water content between the crusted and non-crusted soils between water potentials of – 10000 cm and – 500000 cm (Figure 6.6).

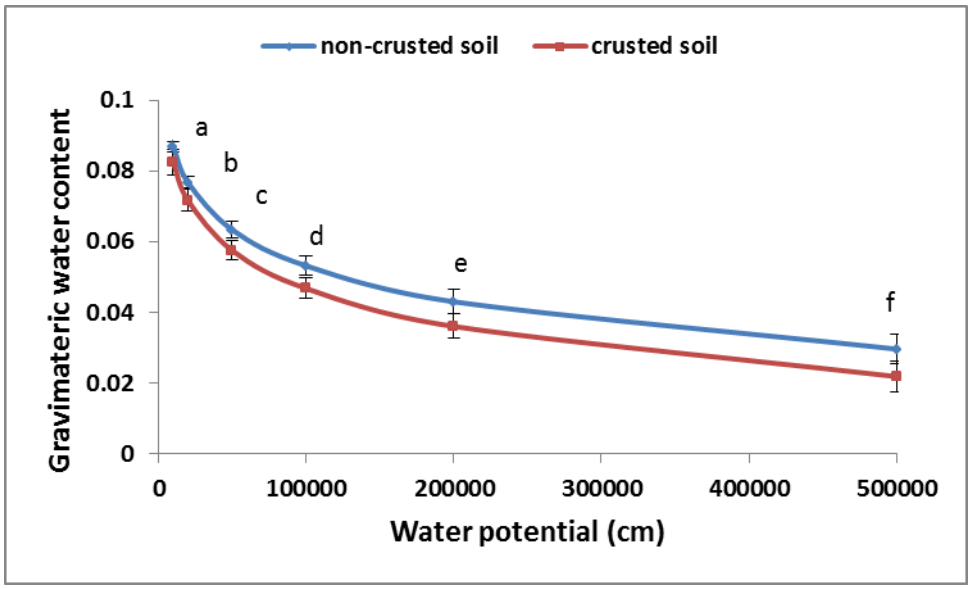


Figure 6.6. Water retention curve for crusted and non-crusted soil determined by WP4C. Bars indicate ±1 standard error.

6.3.7 Values of van Genuchten parameters

The RETC derived function of K(ψ) data and HYDRUS 2D/3D inverse solution of K(ψ) data resulted in considerable differences in predicted VGM parameter values and soil water retention curves (Figure 6.7). Hydraulic conductivity estimated by HYDRUS 2D/3D and RETC were approximately twice that measured at – 0.5 cm tension by the minidisk infiltrometer.

The α values estimated by RETC were substantially lower than that estimated by HYDRUS 2D/3D at all sampling dates. Between day 1 and day 71, HYDRUS 2D/3D indicated α decreased only slightly over time from 0.135 to 0.099. In contrast, RETC indicated that α decreased substantially from 0.103 at day 1, to 0.007 at day 8, then remained almost constant between day 8 and day 71.

The *n* values were similar between the two approaches at all dates, values ranged from 1.38 to 1.58 for HYDRUS 2D/3D, and from 1.28 to 1.57 for RETC. Total porosity calculated from bulk density was substantially higher than the θ_s estimated by HYDRUS 2D/3D at all sampling dates. The θ_s value determined by HYDRUS 2D/3D decreased from 0.40 at day 1, to 0.26 at day 8, and to 0.22 at day 71.

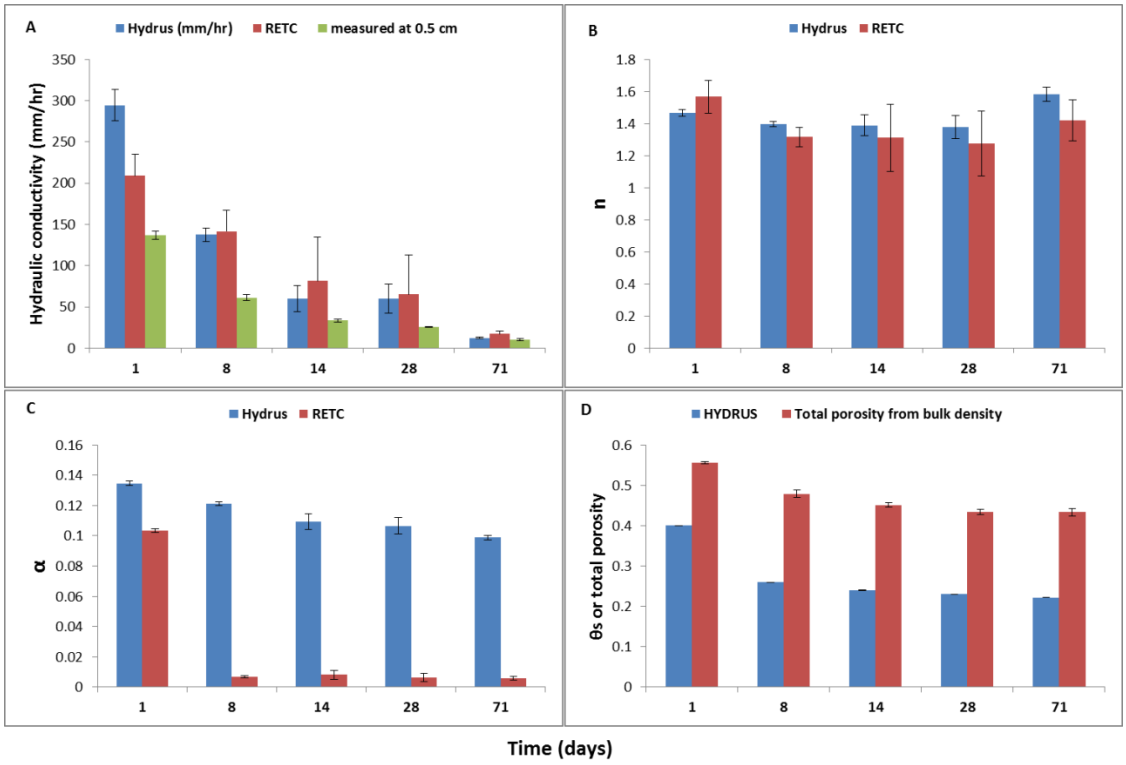


Figure 6.7. Values of van Genuchten parameters determined by HYDRUS, RETC and minidisk infiltrometer at 0.5 cm, and the total porosity obtained from bulk density. Bars indicate ±1 standard error in parameters fit, as calculated by RETC and HYDRUS for average data pairs.

6.3.8 Predicted water retention curve from HYDRUS 2D/3D and RETC

Predicted water retention curve had the same moisture content at suction head zero cm, as the θ_s value was used to construct both water retention curves (Figure 6.8). Overall, both approaches demonstrated that the retention curve for day 1 (prior irrigation) was substantially different to that of the other measured dates, which demonstrates the fundamental difference between the non-crusted (day 1) and crusted soil surface (day 8

– 71). Over the experimental period, substantial differences in retention function existed between the two approaches. For example, at a suction head of – 100 cm water potential, the moisture content at day 8 was 0.24 cm/cm for the RETC approach, compared with 0.15 cm/cm for HYDRUS 2D/3D.

The retention curve between day 1 and day 8 determined by RETC indicated crust formation reduced the presence of pores larger than 150 µm (ψ= - 20 cm) and increased the numbers of pores smaller than 150 µm, whilst HYDRUS 2D/3D indicates crusting reduced pores larger than 3 µm. Between day 8 to day 71, the retention curves estimated by RETC suggest the soil crusts had most pores between – 20 cm and – 20000 cm suction equal to pore sizes between 0.15 µm and 150 µm, whilst the retention curve estimated by HYDRUS indicates that the soil crusts had most pores between – 3 cm and – 10000 cm equal to pore sizes between 0.30 µm and 1000 µm diameter.

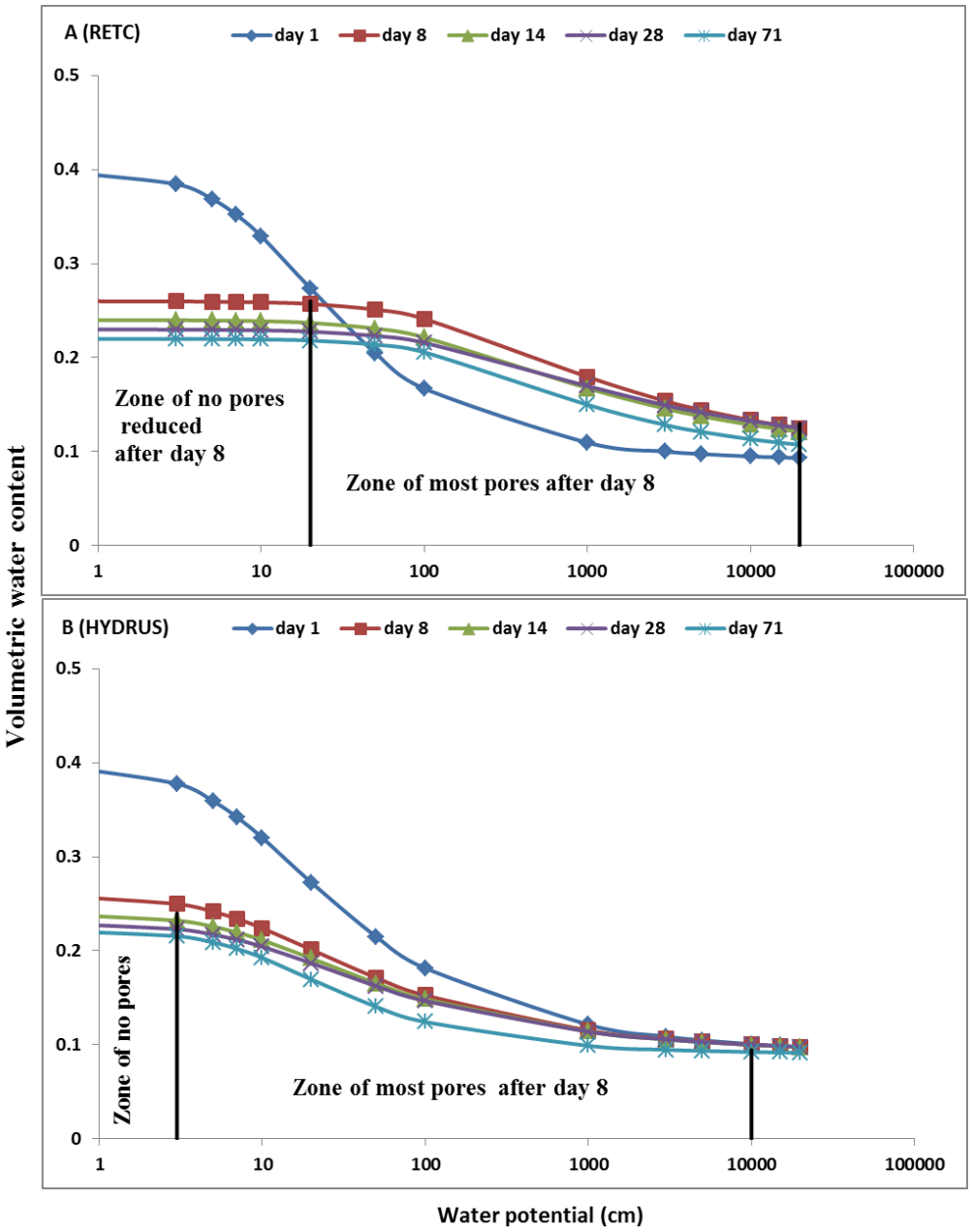


Figure 6.8. Predicted water retention curve from Van Genuchten parameters determined by RETC (A) and HYDRUS (B).

6.3.9 Surface cracking

The crack width and the surface area occupied by cracks increased over time, while the size of the crust segments decreased (Figure 6.9). For example, crack width ranged from 0.46 mm at day 8, to 0.63 mm at day 14 to 1.21 mm by day 71. The size of the crust segments ranged from 61 mm at day 1, to 50 mm at day 14 and 36 mm by day 71. The soil surface area occupied by cracks ranged from 0.56 % at day 8, to 2.73 % at day 14,

and 3.25 % by day 71. Pearson correlation indicated that the width of the cracks was most highly correlated with time (R^2 = 98, P < 0.05). Crack area was highly correlated with soil moisture (R^2 = 99, P < 0.01), whilst no significant correlation existed between the size of crust segments and either time or soil moisture.

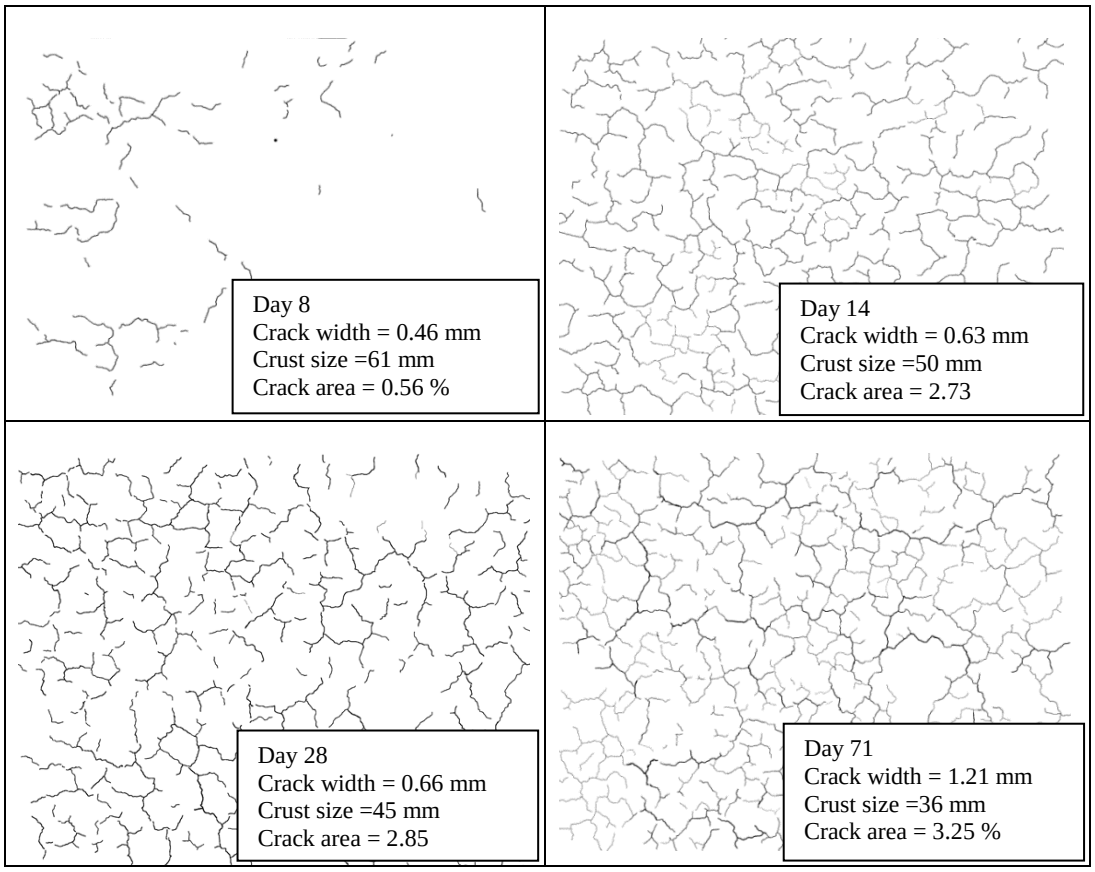


Figure 6.9. The width, diameter and area of soil surface cracks from days 8 to 71.

6.3.10 Image of soil crusting

Image A in Figure 6.10 indicates that the captured section of the upper surface of the soil crust contained pores between 40 – 250 μm in diameter. These pores occupied approximately 2 % of total surface of the crust surface. Image B in the Figure 6.10 indicates that the crust consisted of two layers, in which the upper surface layer had an average thickness 290 μm and a porosity of approximately 3.5 %, whilst the lower layer

was approximately 1800 μm thick and had a porosity of around 15 %. Overall, the soil crust was estimated to have an average porosity of around 14 %.

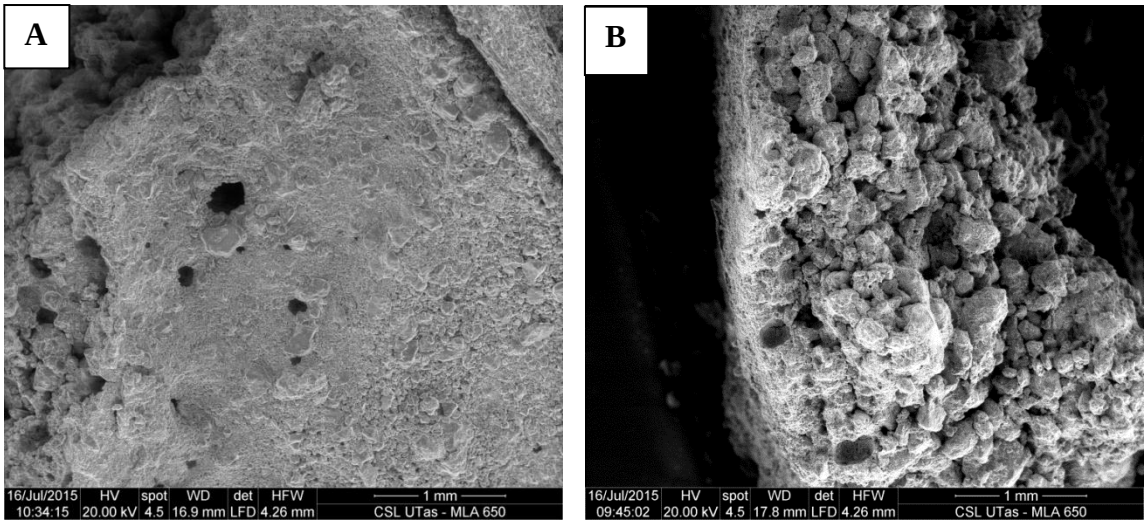


Figure 6.10. Images from scanning electron microscope (SEM) for the captured section of the upper surface and lower layer of the soil crust at day 71.

6.4 Discussion

6.4.1 Crust, structure and formation

The SEM images demonstrated that the soil crust formed 71 days after cultivation consisted of two distinct layers. The upper layer had a porosity of approximately 3.5 %, and was around 290 μm thick, whilst the lower layer had a porosity of approximately 15 %, and was around 1800 μm thick. While these observations are likely to vary between different sections of crust, they are consistent with the model of crust formation proposed by McIntyre (1958), in which a thin compact layer 100 μm thick formed over a more porous washed –in layer up to 3000 μm thick. Image analysis indicated that the total porosity of the soil crust (2000 - 3000 μm thick) was around 14 %.

By day 71, monitoring images at the site demonstrated that the crack width and the size of crust segments were around 1.21 mm and 36 mm, respectively, while the proportion of the area occupied by cracks was approximately 3.25 %. However, the proportion of the area occupied by cracks significantly increased when the soil moisture decreased

6.4.2 Crust total porosity

Determination of the saturated water content, or van Genuchten $\theta_{s,}$ or total porosity proved difficult, with different procedures resulting in different values. The SEM derived porosity of the soil crust 14 %, which was substantially less than the total porosity calculated from bulk density at 43 % (day 71).

The balk density derived value of total porosity is considered to be overestimated, most likely as a result of a sampling too deeply beneath the crust layer, and thus including the more porous soil beneath the crust. Given the very thin nature of the soil crusts, error is also likely to have occurred during the determination of the volume of excavation, as the plastic bag is unlikely to have adequately filled the excavated space (Cresswell & Hamilton 2002). The SEM approach is also prone to error, especially with determining the presence of very small pores and separating soil pores from spaces in which large sand grains have been removed.

Total porosity may also be estimated as being no lower than the final moisture content under the disk infiltrometer at – 0.05 cm, which averaged 24 % and the maximum soil moisture content following irrigation that ranged from 0.25 – 0.34 cm/cm. Estimation of the θ_s parameter from soil moisture monitoring is however prone to error associated with the EC-5 probe being pushed too deeply beneath the crust and including the more porous subsoil, and thus may also be overestimated. Despite use of multiple approaches, we were unable to reliably estimate the total porosity or θ_s of the soil crusts. Based on

the range of approaches, each with its limitations, we estimated the total porosity to have ranged from 20 % to 30 %.

6.4.3 Development of soil crusting over time

Review of the literature indicated that the majority of soil crust formation occurs between the 1st and 10th rainfall events depending on soil properties and the intensity of rainfall or irrigation events (Mellis et al. 1996, Fohrer et al. 1999). Observation of soil condition beneath the Cornell infiltrometer when water was applied at low energy (2 cm) on day 1 before irrigation or rainfall showed that structural crust formation had initiated with very little mechanical or droplet energy presumably via slaking (Plate 6.8).

Determining the point at which a soil crust is said to have fully developed is not straight forward. In this study, we assumed crusts had fully formed once 85 % of the maximum measured value of crusting was reached. Measurements of penetration resistance, crust density, unsaturated hydraulic conductivity at - 0.5 cm (minidisk and tension infiltrometer) and steady infiltration rate (droplets falling from 120 cm height) all indicated that 85 % of crust formation had occurred around the 9th rainfall/irrigation events or the 14th day after cultivation. Castilho et al. (2011) also observed changes in soil surface condition such as density and porosity after 3 rainfall events, while a significant reduction in roughness was reported after 10 rainfall events. However, the Cornell infiltrometer also demonstrated that significant differences in steady state infiltration still existed between the two droplet heights at day 14 and 28, which indicate potential for further crust formation after day 14.

It is apparent that soils at the site are capable of forming soil crusts following a single very low energy rainfall event. Increasing droplet fall height from a height of 2 cm to 120 cm resulted in a 70 % reduction in steady state infiltration rate on day 1 due to the

greater crust formation during the more elevated simulated rainfall. These results indicated that raindrop impact was responsible for considerable disaggregation and soil detachment, which led to reduced soil porosity and water movement (Sumner & Miller 1992, Castilho et al. 2011). An et al. (2012) also reported that sediment yield without raindrop impact (73.75 %) was significantly less than that from with raindrop impact (96.20 %).

Plate 6.8. Initiation of crust formation after measurement of water infiltration by Cornell infiltrometer at 2 cm height on day 1.

6.4.4 Effect of crust formation on soil porosity and pore size

Previous studies have reported that soil crusting has led to a reduction in soil porosity (Vandervaere et al. 1997, Jakab et al. 2013), however little is known about the size range of pores, which are influenced by crust formation. The SEM images indicated that for a dried soil crust at day 71, pore size ranged from 40 µm to 250 µm. The WP4C demonstrated that crust formation did not influence porosity smaller than 0.3 µm (less

than – 10000 cm tension). The tension infiltrometer (200 mm) data between day 1 and day 8 demonstrated that crust formation reduced the proportion of pores equal or larger than 600 µm (Figure 6.11), whilst between day 8 and day 28, crust formation reduced pores equal or larger than 3000 µm. In contrast, the minidisk demonstrated that crust formation reduced the proportion of pores equal or larger than 500 µm between day 1 and day 28, and pores equal or greater than 1000 µm between day 28 and 71 (Figure 6.11).

This discrepancy in the results between two infiltrometers is thought to have resulted from differences in starting point, wetted area and weight of the two devices. The tension infiltrometer started with – 15 cm while the minidisk infiltrometer started with – 6 cm. The two devices also differed in infiltration area, in which the base of tension infiltrometer is 200 mm diameter verses 45 mm diameter for the minidisk infiltrometer. The weight of the 200 mm diameter tension infiltrometer may have reduced flow through layer pores compared with the minidisk. Both procedures indicated that there was a significant reduction in pore size over time, which resulted in reduced soil hydraulic conductivity, as supported by previous studies (Zhang et al. 2001, Bachmann et al. 2006, Osman & Barakbah 2006, Hyatt et al. 2007).

6.4.5 Effect of crust formation on water movement

A review of the literature indicated that a significant reduction in soil hydraulic properties occur when soil porosity reduced, resulting from crust formation (Vandervaere et al. 1997, Chahinian et al. 2006, Souza et al. 2014). In this study, results showed that between day 1 to day 71 the unsaturated hydraulic conductivity at – 0.5 cm tension determined by minidisk infiltrometer decreased from 137 mm/hr to 10 mm/hr, whilst that determined by tension infiltrometer decreased from 203 mm/hr to 3 mm/hr.

Moreover, steady state infiltration rate with a droplet height a 2 cm decreased from 474 mm/hr at day 1, to 33 mm/hr by day 71, whilst steady state infiltration rate with a droplet height of 120 cm decreased from 178 mm/hr to 23 mm/hr.

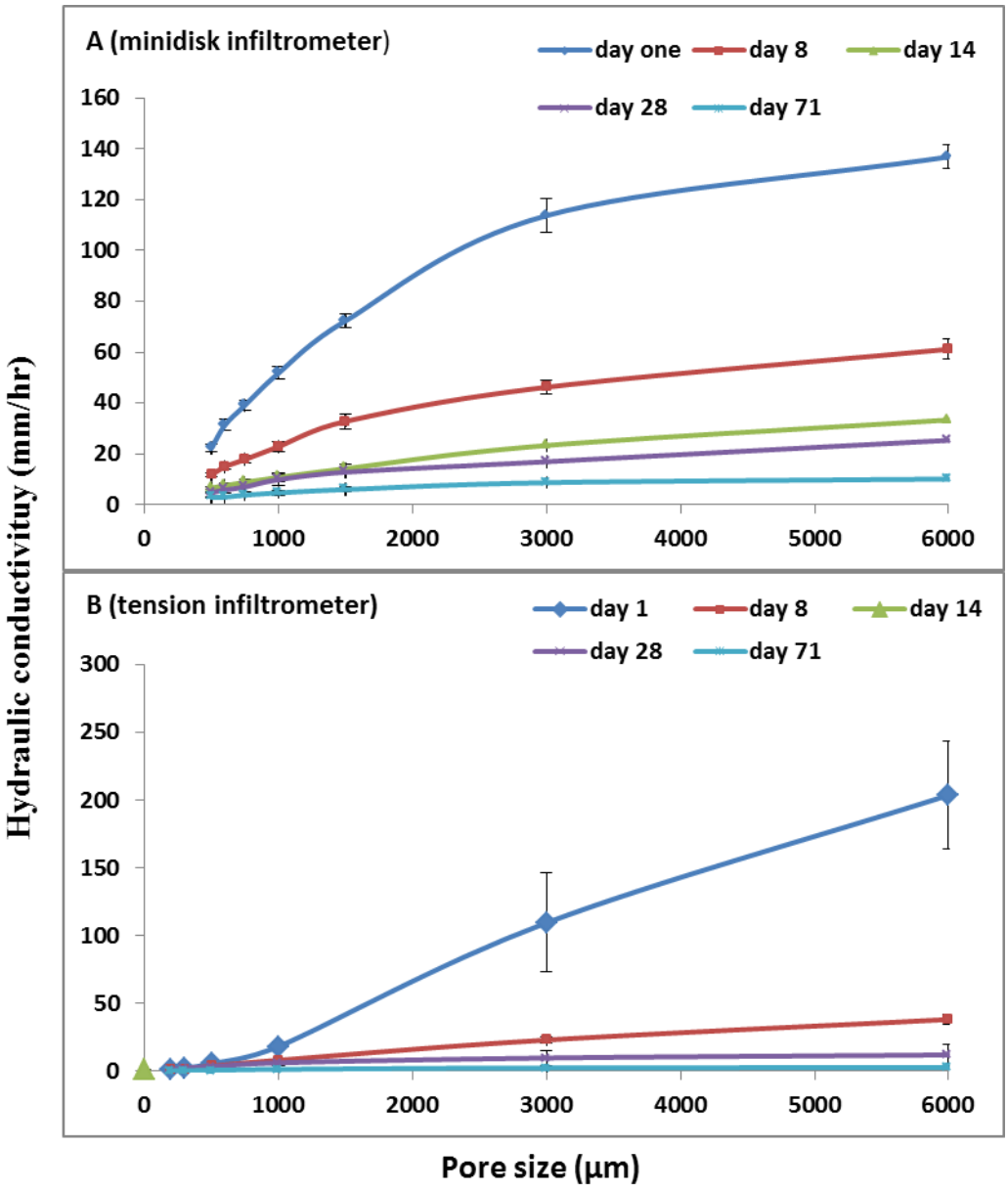


Figure 6.11. Changes in soil hydraulic properties and pore size at each date for minidisk infiltrometer (A) and tension infiltrometer (B). Error bars indicate ±1 standard error.

6.4.6 Determining hydraulic properties for models soil crusts

Simulating the effect of soil crusts in finite element models such as the HYDRUS suite of models requires knowledge of the crust thickness, area of soil surface occupied by soil cracking, saturated hydraulic conductivity and soil water retention curve function. For our site at day 71, SEM images and field sampling indicated crust thickness was in the range of 2 – 3 mm, and cracks occupied 3.25 % of soil surface, which was highly correlated with soil moisture that can be readily accounted for in the model. Saturated hydraulic conductivity determined by the Cornell infiltrometer with a 2 cm fall height was 8.5 mm/hr, whilst near saturated hydraulic conductivity at - 0.5 cm was 10 mm/hr for the minidisk and 3 mm/hr for the 200 mm diameter tension infiltrometer. The HYDRUS 2D/3D inverse solution also indicated that saturated hydraulic conductivity of the soil crusts was 12 mm/hr while the RETC estimation was 17 mm/hr. Consequently, the saturated hydraulic conductivity of crust was around 10 mm/hr, as we suspect the weight of the 200 mm diameter tension infiltrometer may have reduced flow once the soil wet up.

Difficulty was encountered determining the total porosity or saturated water content (θ_s). Results from the moisture probe beneath the disk infiltrometer and soil moisture monitoring at the site suggest that θ_s was in the range of 0.20 – 0.30 cm/cm although we suspect these values may be overestimated due to the probe sensing the more porous soil beneath the crust. In contrast, the SEM images indicated crust porosity of around 14 %, which appeared to be too low. The WP4C indicated that θ_r for both the crusted soil and the non-crusted soil was in the range of 0.08 g/g, however without confidence in the measurement of crust density, this value was difficult to convert to a volumetric basis. Assuming a bulk density of 1.75 g/cm^3, the θ_r determined from WP4C would be around 0.14 cm/cm.

HYDRUS and RETC values of *n* were similar at all dates in the range of 1.28 to 1.58. A major discrepancy existed between the RETC and HYDRUS 2D/3D estimations of the α parameter. Prior to crust formation the α values for RETC (0.10) and HYDRUS (0.13) were similar, however by day 8, RETC estimated α was around 0.007, whilst HYDRUS estimated α was greater than 0.10 when the VGM values are plotted. Consequently, more confidence was placed in RETC estimation of α and n parameters than HYDRUS, as the effected pores determined by minidisk were closer to RETC than to HYDRUS 2D/3D.

6.5 Conclusion

Results indicated that soil crusting had largely formed after the 9th rainfall event. SEM analysis found that the crust consisted of two thin distinct layers. The upper layer was 290 µm thick and had around 3.5 % porosity while lower layer was 1800 µm thick and had around 15 % porosity. Values of total porosity varied considerably according to methodology from 14 % (SEM images) to 43 % (from bulk density). The SEM analysis indicated that the pore size range of the fully crusted soil was between 40 – 250 µm, whilst the minidisk infiltrometer indicated that crusting affected pores greater than 500 µm between day 1 and day 28. Reduction in total porosity and pore size resulted in the decrease of soil hydraulic conductivity, which was observed by all approaches.

The main difference in VGM parameters estimated from HYDRUS 2D/3D and RETC was in the range of affected soil pore sizes. RETC indicated that soil crusting reduced soil pore greater than 150 µm while HYDRUS indicated that soil crusting reduced pore size greater than 3 µm. We recommend that hydraulic conductivity and *n* to be estimated by RETC rather than HYDRUS 2D/3D from infiltration data at multiple matric potentials using the minidisk infiltrometer. The θ_r value should be determined by

multiple WP4C readings below 15000 cm, whilst the α and θ_s values require further research.

Chapter 7: General discussion

7.1 Soil crusting

Soil crusting is worldwide phenomena that occurs in variety of soil types and conditions (Sumner & Miller 1992). Crusting reduces water infiltration, leading to increased runoff and erosion and reduced seedling emergence (Awadhwal & Thierstein 1985, Assouline & Mualem 2001, Carmi & Berliner 2008, Chamley et al. 2012). Given the potential for soil crusting to influence hydrological process, agricultural production and the environment, soil crusting has not received adequate research attention, and much remains unknown or poorly understood.

Soil management practices at the Houston's farms, in southern Tasmania, Australia, have led to loss of soil organic carbon, which has increased surface crusting, which in turn has resulted in poor irrigation efficiency, runoff, erosion and blocking of furrows with sediment and waterlogging (Chamley et al. 2012). By investigating the process of disaggregation and the influence of soil chemical and physical properties on aggregate stability it was anticipated that options for reducing crusting at Houston's farms would be identified.

7.2 Measuring aggregate stability

The susceptibility of soil to disaggregation and crust formation was explored by comparing aggregate stability at 20 sites distributed across the five properties used by Houston's farms for packet salad production. As there is no standard method by which susceptibility to soil crusting is routinely assessed, we measured aggregate stability by wet sieving (WS), rainfall simulation (RS), ultrasonic vibration (UV) and clay dispersion. All methods of determining aggregate stability demonstrated aggregate

stability varied widely across the five farms. For example, aggregate stability determined by WS ranged from 28 % to 73 %.

Results indicated the four different procedures were only moderately correlated with each other. This is likely to have resulted from each of the different procedures applying different types and levels of disruptive energy, as such each approach favoured aggregate breakdown by different mechanisms, or placed greater emphasis on some processes compared with others. Consequently, selection of a procedure to measure aggregate stability needed to consider the type of disruptive forces and disaggregating processes that field aggregates are subjected to. As no one method was able to adequately simulate the expected range of disaggregation mechanisms experienced by soils at Houston's sites, we concluded that consideration should be given to determining aggregate stability using multiple procedures and multiple moisture pre-treatments in order to reveal the maximum extent of differences between sites and or treatments.

7.3 Measuring soil crusting

Measuring the severity or degree of soil crusting was not straight forward. We inferred the severity of crusting from penetration resistance, crust density and soil hydraulic conductivity. All measures of crust severity were moderately to highly correlated with each other ($R^2 = 0.57 – 0.80$), however, their ability to discriminate between treatments differed. The crust density approach had the lowest ability to discriminate between treatments while hydraulic conductivity had the highest ability to discriminate between treatments. Hydraulic conductivity was the most time consuming procedure, requiring the highest level of skill to operate, and was poorly correlated with the other approaches. We found penetration resistance to be the simplest and most rapid test to perform, hence providing a precise and reliable means for growers such as the Houston to monitor crust

severity. The proviso is that soils must be measured at similar moisture content that is normally the case for soil crusts.

7.4 Mechanisms of aggregate breakdown

The processes responsible for aggregate breakdown were explored by comparing aggregate stability determined by a range of procedures, moisture pre-treatments and wetting fluids (distilled water, irrigation water, 0.02 M $CaCl_2$ solution, 5 % sodium hexametaphosphate and kerosene). Results indicated that raindrop impact was important for initiating aggregate breakdown due to the mechanical energy of the impacting raindrops, as supported by Jimba and Lowery (2010).

Determination of the relative contribution of rain drop energy compared to that of slaking and or dispersion was difficult to estimate. The energy associated with raindrop impact occurred simultaneously with rapid soil wetting, which acted together to produce a greater degree of aggregate breakdown than raindrop impact or aggregate immersion alone.

Comparison between the RS and WS procedures indicated that raindrop impact resulted in approximately 14 % disaggregation, which neither the WS or UV procedures simulate. Moreover, aggregate stability determined by RS was 10 % higher than WS in the 0.02 M $CaCl_2$ solution, indicating that approximately 10 % of disaggregation resulted from raindrop impact in the absence of dispersion. The difference in aggregate stability between distilled water and kerosene indicated that around 44% of the aggregate breakdown resulted from clay swelling, whilst only around 1% soil disaggregation resulted from air compression. Consequently, approaches to reduce soil crusting needed to consider the physical effect of raindrop impact as well as slaking by clay swelling and to less extent clay dispersion.

7.5 Crust formation

Crust formation and surface sealing were observed to occur during the first soil wetting event when water was applied with very low energy via the Cornell infiltrometer 2 cm height. Multiple techniques including penetration resistance, crust density, unsaturated hydraulic conductivity and steady infiltration rate indicated that around 85 % of the maximum crust formation occurred after the 9^{th} rainfall and/or irrigation event equal to about day 14 after bed preparation under normal irrigation practice at Houston's farms. This finding is supported by Mellis et al. (1996) and Fohrer et al. (1999) who also reported that soil crusting formed between the 1^{st} and 10^{th} rainfall events.

The SEM analysis indicated that soil crusts consisted of two distinct layers, in which the upper layer had a porosity of 3.5 % and 290 µm thick while lower layer had a porosity of 15 % and 1800 µm thick. These findings are in agreement with McIntyre (1958) who reported that soil crusting consisted of two thin layers namely upper layer 100 µm thick and washed – in layer 3000 µm thick.

7.6 Management of soil crusting

The variation in soil crusting at Houston's farms offered the opportunity to explore how chemical, physical and mineralogical properties influenced aggregate stability and crusting. The survey of soil properties and aggregate stability across the five farms found that the type of soil properties associated with aggregate stability differed between the three methods used for measuring aggregate stability. Aggregate stability determined by RS was related to soil properties associated with aggregation, namely ECEC and the proportion of polyvalent cations (Ca^{2+}, Al^{3+}), whilst aggregate stability determined by WS was more closely related to soil properties associated with disaggregation, namely sand and quartz content and to a lesser extent the proportion of

monovalent cations and organic carbon (MCAR, EPP). Clay dispersion was related to factors active in re-aggregation and flocculation, namely pH, quartz content and different measures of particle size (clay, silt and sand).

Options for improving aggregate stability and preventing soil crusting appeared to be limited as aggregate stability was most closely associated with inherent soil properties, which cannot be readily changed. Results from the previous survey (Chapter 3) indicated potential for Ca^{+2} and organic based products to reduce crusting. These were included in two replicated field trials together with a range of available commercial products that were claimed to be able to improve soil aggregation or reduce crusting.

7.6.1 Gypsum

The positive relationship between aggregate stability and polyvalent cations such as exchangeable Ca^{2+} indicated potential to improve aggregate stability through application of products such as gypsum or lime. Gypsum was applied as a single amendment (0.5 kg/m^2) in the preliminary experiment (Chapter 4) and at two rates of 0.25 kg/m^2 and 0.5 kg/m^2 and in combination with paper waste, phosphoric acid and wire mesh in a second experiment (Chapter 5). Results indicated that the gypsum significantly reduced soil crusting relative to the control, especially in combination with the paper waste and phosphoric acid. This reduction in soil crusting was attributed to increased flocculation, resulting from Ca^{+2} having greater charge density than monovalent cations (Hanay et al. 2004, Bennett et al. 2014), and increased electrolyte concentration, which reduced clay swelling (Chan 1995).

7.6.2 Soil carbon and paper waste

SOC was only moderately and somewhat inconsistently associated with aggregate stability while labile carbon was consistently poorly associated with aggregate stability.

This finding is in contrast to the extensive literature that strongly relates aggregate stability to SOC, or measures of labile carbon (Tisdall & Oades 1982, Chenu et al. 2000, Loveland & Webb 2003). We postulate the lack of a relationship between labile carbon and aggregate stability, and the poor to moderate relationship between SOC and aggregate stability was due to the presence of recalcitrant forms of carbon, which were not actively involved in soil aggregation.

Extensive literature has demonstrated the ability of organic carbon waste and compost to increase soil carbon and aggregate stability (Tisdall & Oades 1982, Tejada & Gonzalez 2003, D'Hose et al. 2014). However, at the Houston's farms, use of animal waste based compost is not allowed due to strict food safety protocols. As such we sourced news print-paper waste as an organic soil amendment. The paper waste was applied as a single rate at 8 kg/m^2 in the preliminary experiment (Chapter 4), and at 1.0 kg/m^2, 2.5 kg/m^2 and 7.5 kg/m^2 or in combination with gypsum and or phosphoric acid in the second experiment (Chapter 5).

Results indicated that paper waste was the most effective product for reducing soil crusting as measured by hydraulic conductivity, crust density and penetration resistance. This reduction in crusts using the paper waste treatment also significantly improved seedling emergence and crop yield. The reduction in soil crusting in the paper waste was attributed to its high carbon content (50 %), high Ca^{+2} content (3292 ppm) and physical presence in soil, which may have reduced raindrop impact or slowed rates of wetting. Results indicated that the greatest reduction in soil crusting was achieved when the paper waste was incorporated into the soil surface along with phosphoric acid and gypsum.

7.6.3 Phosphoric acid

Phosphoric acid was applied at a single rate (75 ml/m^2) in the preliminary experiment (Chapter 4), and at 80 ml/m^2 and 160 ml/m^2 and in combination with paper waste and gypsum in the second experiment (Chapter 5). Results indicated that phosphoric acid improved aggregate stability, crust density and soil hydraulic conductivity, especially when included with the paper waste. This reduction in soil crusting and increased aggregate stability were attributed to dissolving surface soil carbonates and formation of soluble Ca and Mg phosphates that act as aggregating agents.

7.7 Physical properties of soil crust

The physical properties of soil crusts are not well understood. Furthermore, crusting is not included in most soil water models. In this thesis we attempted to determine the physical properties, specifically van Genuchten parameters of a 71-day old soil crust. Uncertainly remains as to the pore size affected by crust formation. Results from the minidisk indicated that crusting reduced soil pores greater than 500 µm. The SEM images indicated that when soil crusting had fully formed, pores ranged between 40 – 250 µm. The fitting of the k (ψ) data by RETC indicated that crusting reduced soil pores greater than 150 µm, while results of the inverse solution of step wise infiltration using HYDRUS 2D/3D indicated that soil crusting reduced pores greater than 3 µm.

Difficulty was also encountered with determining the VGM parameters including θ_s and α, as different approaches resulted in considerably different values. For example, values of θ_s or total porosity ranged from 14 to 43 %. The θ_r parameter was adequately determined by WP4C. The *n* and hydraulic conductivity could be estimated using HYDRUS or RETC in which *n* value ranged from 1.42 to 1.58, and hydraulic

conductivity ranged from 12 to 17 mm/hr at day 71. Further research is required to estimate the α and θ_s parameters.

7.8 Managing soil crusts at Houston's farms

The following recommendations are made to minimise the formation of alternatively ameliorate soil crusts at Houston's farms: (1) substantial surface crusting occurred during the first rainfall or irrigation event such that periodical mechanical destruction of the crust is not likely to be effective management procedure, (2) monitoring of crust severity can be cheaply and effectively conducted by measuring penetration resistance, (3) significant improvement in soil crusting can be achieved through application of gypsum, paper waste and phosphoric acid, (4) gypsum should be applied at 0.50 kg/m^2 prior to sowing, (5) as the phosphoric acid treatment was observed to have only improved crusting in the 14 days after application, phosphoric acid should be added to the soil at approxiametly160 ml/m^2 immediately after sowing. This will require adjustment to current phosphate fertilizer practice and (6) paper waste should be added to soil at 7.5 kg/m^2 periodically i.e. yearly to help maintain soil quality.

Chapter 8: General conclusion

Formation of soil crusting at Houston's farms has resulted from frequent and intensive cultivation. The structural properties of the crust layers were considered to be similar to what had previously been reported in the literature, where a thin, dense layer formed having very low total porosity and pore size. This layer of soil crust resulted in considerable reduction soil hydrological properties, for instance soil hydraulic conductivity was more than 14 times lower for crusted soil than non-crusted soil.

Methods of aggregate stability were poorly correlated with each other as each method simulated a different type and level of disruptive energy. Aggregate breakdown principally resulted from raindrop impact, clay swelling, followed by dispersion with minor contribution from air compression and mechanical abrasion. Selection of an appropriate method for measuring aggregate stability should match the field conditions. As such, we found the stability of soil aggregates at Houston's farms was best assessed using the rainfall simulation procedure on air dried aggregates.

The different approaches for measuring the severity of soil crusting were highly correlated with each other, in which penetration resistance was found to have good precision and ability to discriminate between sites when conducted at similar moisture content. We recommended use of penetration resistance for routine measurement of crust severity provided soils are at similar moisture content.

Crust formation was related to a wide range of soil properties, most of which were inherent soil properties such as sand and quartz content. This made options for improving aggregate stability and reducing soil crusting limited. Aggregate stability was also related to polyvalent cations such as Ca^{+2} and to less extent soil organic carbon. Field experiment evaluated nine products at different rates and combinations, however

no single amendment was able to prevent the development of soil crusting at the site. However, a significant reduction in crusting resulted from application of paper waste and gypsum as single products or in combination with phosphoric acid. Phosphoric acid also significantly reduced soil crusting in the two weeks following application. Consequently we recommended regular application of gypsum (0.50 kg/m^2) and phosphoric acid (160 ml/m^2) should be applied to the soil at the farm prior and after sowing, respectively. In addition, paper waste should be added to soil periodically i.e. yearly, to help maintain soil quality.

Techniques for determining the physical properties of surface crusts are not yet fully resolved. Minidisk analysis and RETIC fitting of $k(\psi)$ data indicated that crusting reduced pores lager than 500 µm and 150 µm respectively while HYDRUS 2D/3D indicated that crusting reduced pores larger than 3 µm. Difficulty was encountered determining the θ_s and α VGM parameters while θ_r was adequately solved using WP4C, and *n* was able to be solved by either the RETC or HYDRUS procedures. Further research is required to evaluate the alternative approaches for determining of θ_s and α.

This thesis conclude that

1. Soil crusting formed after the first rainfall event, and that 85 % of the maximum crust formation occurred after the 9^{th} rainfall event.
2. Slaking by swelling and raindrop impact followed by clay dispersion were the main mechanisms responsible for aggregate breakdown
3. Aggregate stability should be determined by rainfall simulation for soils at the Houston's farms.

4. Penetration resistance procedure is recommended for monitoring the development of soil crusts and to discriminate between different treatments in future experiments.
5. Application of a large range soil amendments were not able to prevent soil crusting, however, significant reduction in soil crusting was made with paper waste and gypsum, and over the first 14 days with phosphoric acid.
6. We demonstrated the potential for RETC and HYDRUS procedures to estimate the *n* and soil hydraulic conductivity VGM parameters from k(ψ) minidisk infiltration data.

Future work is required to

1. Further evaluate different rate, timing and frequency of paper waste and gypsum for reducing crusting over a broad range of soil types.
2. Evaluate new products for reducing soil crusting as they become commercially available.
3. Pursue the advancement of a crusting routine in soil water models based on research presented in this thesis.
4. Test the variance in aggregate stability and soil properties using different range of soil fractions.
5. Evaluate further procedures for estimating of VGM θ_s and α parameters.

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